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MANAGING THE TRANSITION BETWEEN BASIC PRODUCTION TECHNOLOGIES:

A Case Study and Generic Lessons

by

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MANAGING THE TRANSITION BETWEEN BASIC PRODUCTION TECHNOLOGIES:

A Case Study and Generic Lessons

I. INTRODUCTION

The success of a high technology firm depends on the output of its research and development (R&D) activity. As advancing technology and increasing competition lead to ever shorter product life cycles, the firm needs a continuous flow of new products. The new products must satisfy both the customer's need for reasonable price and high product performance and the firm's need for low manufacturing (recurring) and development (non-recurring) costs. A firm that fails to develop the proper products will quickly find itself in trouble. In a recent Business Week article, an analyst from Kidder Peabody remarked, "There is great pressure on companies to incorporate the latest technology into new products to reduce cost and get margins up."[1] A former Vice President of NCR further highlighted the urgency of new product development when he stated simply, "If you design using old technology, you can't recover from that."[2]

This paper presents a new perspective on the problem of R&D productivity. The approach used in the paper centers on the concept of a technological generation, or what will be called an "architecture." An architecture is a basic engineering process that, when completed, provides a generic technological framework for the

development of one or more related products. An architecture is the technological base on which a customer product is built. For example, in the case of the firm that is discussed in this paper, an architecture is a series of semiconductor chips that are designed for one of the firm's product lines.

The utility of an architecture diminishes over time. At the beginning of its life, an architecture can be easily adapted to the requirements of customer products. The firm can effectively develop products with correspondingly low manufacturing and development costs. Eventually, the firm begins to reach the limit of an architecture's usefulness. New product development becomes slower and more costly as the technological problems faced by the development group grow more complex. Cost and schedule overruns may become increasingly common. The combination of high manufacturing cost and price competition erodes the profit margins earned on new products.[3]

As the architecture reaches the end of its useful life, the firm faces a technological discontinuity of some significance. The technological discontinuity stems from the firm's need to develop a new architecture that lowers both development and manufacturing costs to yield profits consistent with hurdle rates. The process is discontinuous because the new architecture must embody a substantial "leap" in technology, not just a gradual evolution. Additionally, a new architecture is invariably quite expensive and time-consuming to develop, compared to the previous generation.

The paper argues that the process of transition to a new architecture is one of the key policies that determines R&D productivity. Moving across a technological discontinuity can be likened to the situation of Western settlers who are being chased by wild Indians. The settlers are pursued to the edge of a deep chasm and cannot retreat without being slaughtered. The settlers' chances of survival rest on how efficiently they manage to leap the chasm. This paper focuses on the policies that determine the firm's success in bridging the technological chasm and stay ahead of the Indians (competitors).

The paper is organized as follows. The first section examines a specific firm's problems with R&D productivity. Information about the firm was gathered during a nine month consulting project that addressed declining R&D output. Specifically, the study dealt with cost and schedule overruns in the development of new products. The analysis of rising product development times led to the consideration of the architectural development process. The company feared that the architecture under development for its largest product line would be finished much too late. The firm also planned to start a new architecture in its second largest product line and was interested in how it could better manage the transition. The analysis in the paper is based on the experience of the firm.

The second section distills the information gathered about the firm into a system dynamics simulation model. The model draws

heavily on the firm's experience and includes many of the factors that determine the success of an R&D program. The model serves two important purposes. First, it embodies an explicit organizing framework of the mechanisms that influence R&D productivity. Second, the model serves as a laboratory tool for testing alternative R&D policies. The second section describes the important feedback loops that cause the problem behavior and explains how the feedback loops are represented in the model. The third section presents the "base run" simulation and gives a detailed explanation of the model's behavior.

The fourth section presents and analyzes the policy tests performed with the model. Simulations of the model isolate policies that can significantly improve R&D productivity. For example, model-based analysis reveals that shortening the delay between completion and implementation of a new architecture is extremely important. Second, the model policy changes derived from the model are translated into real, operational recommendations. The specific recommendations were designed in conjunction with one of the firm's senior managers.

The fifth and final section presents the conclusions of the study. Two important conclusions are drawn from the analysis. First, relatively simple and practical policies can dramatically improve R&D output and the firm's overall profitability. Second, often-used measures for evaluating the success, or the prospects for, success of a high technology firm, such as simple return on investment, are

extremely misleading. However, improved measurement schemes are available and are discussed.

II. PROBLEM DESCRIPTION

This section presents the background required to analyze the tradeoff between non-recurring and recurring costs. For simplicity, the subsequent analysis focuses on the firm's dominant product line. The firm produces three groups of products in the data communications industry. One of the product lines generates a majority of the firm's revenue. The dominant product line is the most significant determinant of profit over the 1975-1987 time frame analyzed in this paper.

The manufacturing cost of products in the dominant line depends heavily on advanced semiconductor technology. Enhanced semiconductor capability has allowed dramatic reductions in manufacturing cost with concomitant improvements of product quality.

Development of an architecture based on the large-scale integration (LSI) semiconductor technology fueled substantial increases in the firm's profit. In 1975, the firm was the first in its industry to offer products based on an LSI architecture. The LSI products had a manufacturing cost that was low enough to produce margins of 75% for a new product. A 75% margin means that the product's manufacturing cost (including parts costs, labor, and testing) is only 25% of the sales price. Figure 1 illustrates the growth of profit from 1975 to 1979. The profit figures beyond 1980 are the firm's own projections.

Price competition has slowed the growth of the firm's profit since 1975. The firm faces several formidable competitors who have mounted substantial investment programs. Investment in new architectures has also allowed competitors to reduce their manufacturing costs. Several prominent firms have chosen to compete on the basis of price. The firm has adopted a policy of matching price cuts and consequently its average product price has been falling by about 10% per year since the late 1970s.

Profits are expected to grow rapidly following the completion of new products based on a new architecture in late 1981 or early 1982. The firm has responded to slipping profit by investing millions of dollars and many man-months of engineering talent in an architecture based on the next generation semiconductor technology. The new semiconductor technology is called very large-scale integration (VLSI). The VLSI products will have a manufacturing cost that is projected to be one-third the manufacturing of an LSI product. The projected increase in profit from 1981 to 1987 shown in Figure 1 depends on the completion of the VLSI architecture.

III. DESCRIPTION OF KEY FEEDBACK LOOPS

This section describes some of the important feedback loops contained in the model. The model includes sectors that control the hiring of engineers and managers, the development of new products, and the process of building a new architecture. The description presented below concentrates on the structure essential to analyzing the transition to a new architecture. A more complete description of the full model can be found in Richardson.[4]

Analysis of the technological discontinuity and R&D productivity requires a unifying framework. The paper uses the organizing concept of a feedback loop. A feedback loop exists when a situation leads to a decision that feeds back to affect the situation. There are two kinds of feedback loops, positive and negative. A positive feedback is self-reinforcing and corresponds to the notion of a "vicious circle". For example, the development of new products generates profit that in turn leads to the development of new products. A negative feedback loop is "goal seeking" or "self regulating". For example, declining profit margins create a pressure to develop a new architecture to improve long-run profit margins. This section discusses the positive and negative feedback loops that are important in analyzing the transition between successive architectures.

A. Regenerative Feedback Loop

The firm's dominant characteristic from 1975 to the present has been rapid growth. The firm has experienced revenue growth ranging from 25% to 50% per year. As explained above, the rapid growth of revenue has been accompanied by a substantial increase of profit. The following analysis analyzes the positive feedback loop that controls the growth of the firm.

The growth of the firm depends on continuous investment in new products. Investment in product development eventually leads to product completions. New products generate revenue which results in profit that can be invested in additional revenue-producing products. The resources spent on development regenerate themselves through the earnings of new products. This process is a regenerative feedback loop.

Figure 2 illustrates how the regenerative loop is represented in the model. The model description begins with products in production (PIP) and moves in a clockwise direction.

Products in production (PIP) is the set of items that the firm has available to sell. For example, if the firm had five different products to sell, the value of products in production would be five. Products in production are depleted by the product obsolescence rate (POR) which represents the declining salability of products over the course of their life cycle.

Market share (MSH) depends on products in production (PIP) and the number of products competitors have in production (CPIP). The firm designs specific products in a given product line to meet a variety of customer needs. Consequently, the model assumes that products in production consist of products with somewhat different features and capabilities. An increase in products in production allows the firm to service a larger fraction of the market for a given product line. The model assumes that competitive products in production grow at a rate that is determined outside the particular firm being modelled.

The firm's revenue (REV) is determined by the size of the market (MKT), market share (MSH), and average product price (PRICE). The market is measured by the number of units demanded per year and grows at an exogenously determined rate. Market size multiplied by market share (MKT*MSH) gives the number of units the firm sells per year (SALES).

The firm's pricing policy has been to match the competition and price has quickly followed the competitor's prices downward. Therefore, the model includes a single market price that falls at 10% per year.

The research and develop budget (RDB) is the money allocated to the firm's research and development group. The model equation for RDB is:

RDB = BPD + BA

where

RDB = Research and development budget ($/year)
BA = Budget allocated for architectural development ($/year)
BPD = Budget allocated for product development ($/year)

Each term in the budget equation is discussed below.

The budget allocated for architectural development (BA) is the extra money allocated for the development of a specific architecture. The budget allocated to architectural development is small during the initial stages of architectural development, grows rapidly during the middle stages, and finally declines to zero when the architecture is completed. The spending path for a new architecture mirrors the bell-shaped pattern of effort typical of a large development project.

The budget allocated for product development (BPD) is the money allocated for specific product development projects. The model equation for BPD is:

BPD = REV*FRDB

where

BPD = budget allocated for product development ($/year)
REV = Revenue ($/year)
FRDB = Fraction of revenue allocated to the R&D budget.

The fraction of revenue allocated to R&D represents the common policy of allocating between 5 and 9% of revenue to R&D.

The effect of cost cutting on the budget (ECCB) reduces the product and architectural development budgets if the firm projects it will fail to meet its near-term profit goal. The firm sets a target for pretax return on sales. After examining its anticipated revenues and expenses, the firm estimates its return on sales. Total R&D spending is reduced if the firm believes it will not match its profit goal.

Products supportable by revenue (PSR) is the number of products that the R&D group can afford to work on. Products supportable by revenue is determined by the budget allocated to product development (BPD) and the manpower and capital costs of specific product development projects.

Products in development (PDEV) is the number of products that the firm is developing at a given time. Products in development are increased by the product generation rate (PGEN) if products supportable by revenue are greater than products in development. Products in development are reduced by the product completion rate (PCOMP). The product completion rate represents the movement of products from the development stage to the production stage.

Products in development (PDEV) exist in the development group for a duration called product development time (PDT). Product development time is computed by dividing the product engineering requirement (PER) by the number of engineers working on a product.

The product engineering requirement is the average number of man-months required to develop a product. The number of engineers on a product team is set by the manpower sector of the model.

The product engineering requirement (PER) is affected by the age of the architecture used for product development. The firm anticipates what features will be required in a marketable product. A new architecture is designed to facilitate the desired product specifications. However, the firm cannot know perfectly the range of features that customers will actually demand. Consequently, the architecture will be used in somewhat unanticipated ways. The architecture becomes more difficult to adapt to current product needs as it gets older. The firm believes that after about five years of using an architecture, the product engineering requirement rises substantially, making product development uneconomic.

The age of the architecture also influences the cost of each man-month of product development (CMPD). An old architecture drives costs up by causing less efficient utilization of personnel materials and equipment.

B. Feedback Loops Governing Architectural Development

The model represents two important decisions made about the development of a new architecture. The first decision is when to begin development of an architecture. The firm faces an array of technologies that it can use to develop an architecture. Each

technology has associated with it a non-recurring development cost and a manufacturing cost on derivative products. Over time, general technological progress in the field reduces the expense to the company of reaching a given manufacturing cost using a particular architectural approach. The firm must determine how long to wait for the benefits of general technological progress.

The firm must also decide on the development cost of the new architecture. Given that the firm has decided to begin work on an architecture, it must determine the most desirable combination of non-recurring development cost and manufacturing cost. A technology with a larger development cost will often have a smaller resulting manufacturing cost; in effect, the greater the risk taken, the greater the benefit derived.

A negative feedback loop controls the decision about when to build an architecture. The essence of the negative loop is that falling profit margins and the high cost of new product development using the existing architecture create a pressure that can only be relieved by developing a new architecture. The firm sets a target date for completing a new architecture based on its anticipation that price competition will reduce profit margins to unacceptably low levels. The pressure to start work on an architecture grows as time approaches the target completion date. For example, the firm realized that the margins earned on LSI products would become too low sometime in the early 1980s. The anticipation of unacceptable profits prompted

the firm to start the VLSI architecture in 1979.

Organizational delays generate a counterpressure that discourages the firm from starting an architecture. The firm will be hesitant to start a new architecture until several years after it finished its last architecture. There are several reasons why this is true. First, the firm will want to fully exploit the product opportunities created by the old architecture. For example, the firm spent a great deal of money on the LSI architecture so that it could develop products with low recurring and non-recurring cost. After the completion of the architecture, the firm allocated its resources to the development of the lower-cost products. The firm would not start a new architecture until the majority of the LSI products were approaching the end of their life cycle. The average life of a product is about four years. Secondly, the development of an architecture is an extremely traumatic experience for the firm. Management needs a great deal of convincing before it will fund a new architecture. For example, some managers in the firm thought that LSI would be the last technological breakthrough relevant to the firm's product line. It took time to convince management that VLSI was necessary. The result is that organizational pressures make it unlikely that the interval between the completion of one architecture and the start of the next will be less than four years.

A new architecture must also meet the firm's hurdle rate of return. The firm will not develop an architecture until its projected

return on investment equals at least the hurdle rate.

Once the pressure to build a new architecture outweighs the counterpressures, the firm decides the architecture's development requirements and starts work. The architecture's development requirements are the labor, materials, and other capital resources required to develop the architecture.

The development requirements for a new architecture are fairly inflexible once the firm has selected a technology. For example, in 1979 the firm decided on a plan using the VLSI technology. Subsequent to 1979, general technological progress has made alternative approaches somewhat less expensive to use. However, the cost of reformulating the development plan in order to take advantage of the technological progress would be very high. The cost of changing technologies during an architectural project makes significant revision of the development plan unlikely.

The pressure to develop an architecture is relieved when the architecture is finished. Profit margins on derivative products are restored and the cost of new product development becomes much cheaper. The firm makes no further investment until the pressure for architectural development rises again.

The model represents the negative feedback loop that governs when the firm starts architectural development. Figure 3 shows the

important variables included in the model. The following sections describe each important variable illustrated in Figure 3.

The model draws a distinction between the primary and the secondary architecture. The primary architecture is the technology that the firm uses to develop most of its products. The secondary architecture is the technology the firm uses during the transition to a new primary architecture. For example, the LSI architecture is currently used to develop products. When the VLSI architecture is completed, it will become the primary architecture and the LSI architecture becomes the secondary architecture. The firm will still develop products with the LSI architecture while the VLSI architecture is being implemented. Full implementation of VLSI takes time because the firm must plan the VLSI products and train the engineers in using the new VLSI chip and its related software.

The model represents the pressures faced by a manager who must decide when to start a new architecture. In the model, the decision variable is named the decision to build an architecture (DBA). The decision to build an architecture is a discrete variable that equals "one" if the firm is building a new architecture and "zero" otherwise.

Three pressures influence the decision to build a new architecture. The pressures are the effect of time on the decision to build an architecture (ETDBA), the effect of organizational delay on

the decision to build an architecture (EODDBA), and the effect of return on investment on the decision to build an architecture (ERDBA). Each of the pressures shown in Figure 3 will be discussed below.

The effect of time on the decision to build an architecture (ETDBA) simulates the pressure faced by a manager who knows that profit margins are falling and that new product development costs are rising. Picture a manager who projects that the margin earned on a new product will become unacceptable by 1985. In the model, the date 1985 would then be the reference architectural development date (RFADD). The reference architectural development date is the answer to the question, "when will profit margins on new products fall below an acceptable level?" The model computes the reference architectural development date by examining the manufacturing cost of the current architecture, the anticipated change in price, and the desired minimum profit margin on a new product. The manager then surveys the technological options and realizes that a new architecture cannot be completed until 1986. In the model, the date 1986 is the feasible architectural development date (FADD). The feasible architectural development date is the date on which the firm anticipates completing a new architecture. The factors that determine the feasible architectural development date will be discussed below. The manager would face intense pressure to select the architecture's development requirements and start work. The pressure generated by the effect of time on the decision to build an architecture gets larger as the feasible architectural development date exceeds the reference

architectural development date.

The pressure to begin a new architecture is reduced if the feasible architectural development date is less than the reference architectural development date. For example, consider a manager who projects that a new architecture will be required in 1985. In this case, the reference architectural development date is 1985. Suppose that the manager looks at the technological options and estimates that a new architecture can be finished by 1984. The model assumes that the manager would tend to put off the decision to build the architecture. There are two reasons for this assumption. First, most managers have a natural unwillingness to start multi-million dollar development projects until they absolutely have to. Second, and most important, a delay in deciding to build an architecture may enable the firm to find a less expensive alternative architecture. As previously noted, over time, general technological progress reduces an architecture's non-recurring development cost. The firm cannot perfectly anticipate the pattern of cost reduction but it knows that some progress is likely. If the existing options for a new architecture could be completed before profit declines very far, the risk of waiting is relatively small.

The effect of organizational delay on the decision to build an architecture (EODDBA) reduces the pressure to develop a new architecture. The organizational reasons why management might put off a decision were discussed above. In the model, the effect of

organizational delay is determined by the amount of time since the firm finished its last architecture. The effect of organizational delay reduces the pressure to build an architecture if less than about four years has passed since the firm finished its last architecture. As discussed above, the four years corresponds to the life cycle of products developed with the old architecture. The delaying effect of organizational pressures gradually diminishes with increases in the time since the last architecture was completed.

The effect of return on investment on the decision to build an architecture (ERDBA) models the impact of financial analysis on the architectural investment decision. The effect of return on investment creates a pressure to defer architectural development until its projected return on investment equals the firm's hurdle return on investment. The projected return on investment calculation includes information about the costs of a new architecture as well as the firm's projected sales volume.

The firm allocates manpower and budget to an architecture in development until it is completed. Man-months of investment in an architecture (IA) accumulate in a level of architecture in progress (AP). The firm finishes the architecture when the man-months of effort accumulated in architecture in progress equal the architectural engineering requirement (AER). No further resources are spent on architectural development until the pressures rise high enough to warrant new expenditures.

This section describes the feedback loops that govern the development cost of a new architecture. In the model, the development cost of a new architecture is the architectural engineering requirement (AER) representing the number of man-months required to develop a new architecture, multiplied by the cost of a man-month of architectural development (CMAD). The cost of a man-month of architectural development (CMAD) is the total cost of the materials, capital, and labor for a man-month of architectural development. The following analysis explains how the architectural engineering requirement and the cost of a man-month of architectural development are determined.

The firm must select a combination of manufacturing cost and non-recurring development cost. The firm chooses a combination based on its planned margin (PMAR), the date when it wants a new architecture completed (feasible architectural development date), and its knowledge of the available technologies. Figure 4 illustrates the important variables contained on the model. Each variable shown in Figure 4 is described below.

The planned margin (PMAR) is the margin that the firm anticipates earning on a product developed with the new architecture. The planned margin is adjusted by the change in planned margin (CPMAR). Change in the planned margin (CPMAR) is determined by the discrepancy between the feasible margin (FMAR) and the planned margin. The feasible margin is what can be earned on a new product given that

a new architecture must be finished on or before the planned architectural development date. For example, assume that the firm plans to finish an architecture by 1986. The feasible margin is the largest margin the firm can earn while still finishing by 1986. The change in planned margin adjusts the planned margin downward if the feasible margin is less than the planned margin and vice versa. A goal seeking feedback loop operates to adjust planned margin to the feasible margin.

The feasible architectural development date (FADD) is the date on which the firm plans to have an architecture completed. The change in the feasible architectural date adjusts the feasible date forward or backward. An example illustrates the behavior of the feasible architectural development date. Assume that the firm initially plans to complete an architecture by 1986 and that the products based on the architecture are planned to earn margins of 80%. The firm sends these specifications to the R&D group and the engineers decide that it isn't possible to develop an architecture that earns an 80% margin by 1986. In the model, the firm responds in two ways. First, as discussed above, the firm reduces its planned margin. Second, the firm extends the feasible architectural development date to give the engineers more time to develop an architecture. The added man-months of development investment lowers manufacturing cost and increases the feasible margin. A second goal seeking feedback loop adjusts the feasible margin toward the planned margin through the feasible architectural development date.

The goal for manufacturing cost (GMC) is the firm's desired manufacturing cost for products developed with a new architecture. For example, assume that the firm sets the feasible architectural development date equal to 1986. The firm plans to have a new architecture completed by 1986. The firm anticipates that price will fall by 10% per year from 1981 until 1986. The firm has also set a value for the planned margin. The goal for manufacturing cost answers the question, "what manufacturing cost is required to meet the planned margin in 1986 given that price for the product type will fall by 10% per year?"

The potential architectural engineering requirement (PAER) and the potential cost of a man-month of architectural development (PCMAD) are determined by the goal for manufacturing cost and the state of technology. The model assumes an inverse relationship between the development requirements of an architecture and the manufacturing cost of the products based on the architecture. Within bounds, the more man-months that are invested in an architecture, the lower is the product manufacturing cost. The potential architectural engineering requirement is the number of man-months required to develop an architecture that yields the firm's current goal for manufacturing cost.

A tradeoff exists between both the cost and number of man-months required to develop a new architecture and the goal for manufacturing cost. Lower manufacturing costs can be "purchased" by

increasing development cost. Figure 5 illustrates the tradeoff between the potential architectural engineering requirement and the goal for manufacturing cost. As the goal for manufacturing cost becomes small, further decreases of manufacturing cost require larger increases of the potential architectural engineering requirement.

The tradeoff between development cost and manufacturing cost improves over time due to technological progress. There are two reasons why the cost of reaching a given goal for manufacturing cost (GMC) falls over time. First, entirely new cost-reducing processes are invented. For example, development of the VLSI semiconductor technology dramatically lowered potential manufacturing cost. Second, the cost of an existing technological process falls as "bugs are worked out". For example, the real cost of adopting VLSI would be less if the firm had started in 1981 instead of 1979.

In the model, the variable representing technological change is called the effect of technology (ET). The effect of technology (ET) reduces the cost of reaching a given goal for manufacturing cost (GMC) by a constant percentage per year.

A delay exists between a technological improvement and the firm's perception of the technological improvement. The delay is the time it takes the firm to learn about new cost-reducing technologies. For example, VLSI technology was developed by the semiconductor industry. There was a delay between the development of the technology

and the firm's perception that the technology could be used in its product line. The magnitude of the delay is determined by the amount of communication between the firm and the companies that supply its basic technologies.

In the model, the delay in learning about technologies is called the time to perceive the effect of technology (TPET). The perceived effect of technology (PET) is the delayed value of the effect of technology (ET).

The architectural engineering requirement (AER) and the cost of a man-month of architectural development (CMAD) are the development requirements that the firm finally selects. For example, assume that in the third quarter of 1981, the potential architectural engineering requirement (PAER) and the potential cost of a man-month of architectural development are 120 man-months and $15,000, respectively. The potential architectural engineering requirement and the potential cost of a man-month of architectural development are the requirements of the technology that yields the goal for manufacturing cost (GMC). If the firm starts an architecture during th third quarter of 1981, the architectural engineering requirement becomes 120 man-months and the cost of a man-month of architectural development becomes $15,000.

In sum, the model equations provide a distilled but realistic description of pressures that management face when making decisions about new technologies. Senior managers in the firm have

scrutinized all the important elements of the model. The decision rules included in the model are accurate enough that the firm's Senior Director of Business Planning remarked, "That is exactly the way it happened when we decided to build Generation X." (Generation X is the name of the firm's latest architectural development project.)

IV. ANALYSIS OF THE BASE RUN

This section describes and analyzes the model's base run behavior. The presentation of the base run has two purposes. The first purpose is to illustrate how the important feedback loops interact to produce the problem behavior. Specifically, how do the feedback loops that control the development of new products and architectures cause profits to rise, fall substantially, and then rise again? The second purpose of the base run is to provide a standard of measurement that policy runs can be evaluated against. Several policy experiments will be performed with the model and the results of the experiments will be compared to the base run.

The model's base run begins in 1975 and ends in 1987. The 1975-1987 time frame corresponds to the firm's architectural development cycle. The firm finished the LSI architecture in 1975 and began the VLSI project in 1979. VLSI is scheduled for completion in 1982. The model's time horizon allows analysis of the architectural development cycle beginning with the decision to build an architecture through the completion of the architecture and its associated products.

The model's base run behavior is influenced by four variables that are determined outside the system. The market for the firm's product, as measured in physical units, is assumed to be growing at 15% per year. The average price of the firm's product falls at 10%

per year. General technology reduces the non-recurring development cost of reaching a given manufacturing cost by 20% per year. The number of products offered by competitors grows at 5% per year.[5]

In the base run, the model's initial conditions are set for a firm that has just completed an architecture. The profit margin earned on a new product is assumed to be high and the cost of new product development is assumed to be low.

The model's base run behavior can be divided into three time periods. The distinctions between the three time periods are best illustrated by the behavior of profit. Figure 6 shows the pattern of profit generated by the model. Rapid increases of profit characterizes the first stage of the base run. The first stage begins at month zero and continues until month 27. The second stage of the base run starts at month 27 and ends at month 96. During the second stage, profit growth slows and eventually profit declines. The third stage of the base run begins with the completion of an architecture at month 97. During the third stage, profit continues to fall until month 118. After month 118, profit increase until the end of the simulation in month 144.

This section answers the question, "how do the feedback loops that control product and architectural development generate the base run behavior?" The following analysis focuses on the determinants of profit during each stage of the base run.

The behavior of profit can be best understood by examining a simple accounting equation taken from the model structure. The accounting equation is:

Profit = Sales*(Price*(1-NFROE-FRDB)-AMC) - BA

where

Profit = yearly before-tax profit
Sales = the number of units the firm sells in a year
NFROE = the normal fraction of revenue the firm spends on operating expenses other than R&D
FRDB = the fraction of revenue to the R&D budget
AMC = average per unit manufacturing cost of the products in production
BA = budget allocation to architectural development

The accounting identity defines the relationship between profit and a set of key variables. An increase in the number of units shipped or an increase of price increases profit. An increase in the fraction of revenue to the R&D budget, average manufacturing cost, or the budget allocated to architectural development decreases profit. The normal fraction of revenue spent on operating expenses other than R&D is assumed to be constant. The accounting identity will be used to analyze each stage of the base run.

The number of units sold grows substantially during the first stage of the base run. At the beginning of the simulation, sales grow because the model assumes that the market grows at 15% per year. The initial market-driven increase in sales causes revenue to grow. The firm allocates a fraction of revenue to R&D and the extra R&D budget increases the number of products the firm can afford to develop.

Figure 7shows the increase in the number of products in development (PDEV). The firm eventually completes the products in development and they become available for sale. Figure 7 also shows the increase in products in production (PIP). A larger PIP increases the firm's market share, sales, and revenue.

Average manufacturing cost (AMC) declines during the first stage of the base run. The firm had just completed an architecture at the beginning of the simulation. The manufacturing cost of the products developed with the new architecture are lower than the average manufacturing cost at the beginning of the base run. Average manufacturing cost falls as the low manufacturing cost products are added to products in production.

During stage one, the behavior of profit results from interaction of sales, price, and average manufacturing cost (AMC). The increase in sales and the fall of average manufacturing cost pushes profit up while the decline of price drives profit down. The impacts of sales and average manufacturing cost dominate the effect of price, and profit grows.

As shown in Figure 7, the rate of sales growth slows significantly during the second stage of the base run. The interaction between the age of the primary architecture and the regenerative feedback loop causes the deceleration of sales. New products become more costly as the primary architecture ages. Higher

product development costs reduce the number of products completed for two reasons. First, since each product costs more, a given R&D budget supports fewer products in development. Fewer products in development means fewer product completions. Second, the average product requires more man-months of development effort. The firm completes a smaller number of the more difficult projects. Products in production (PIP) doesn't grow as fast if product completions fall. The growth of products in production declines by enough to lower market share. A smaller market share yields fewer sales and therefore less revenue and profit that can be invested in product development.

The decline of average manufacturing cost (AMC) slows and then stops during stage two. Average manufacturing cost stops falling during stage two because almost all the products in production are based on the new architecture.

The budget allocated to architectural development (BA) increases significantly and then declines during stage two. Figure 8 shows that spending on the architecture follows a bell-shaped pattern that reflects the assumption that development expenditures are relatively low at the beginning and the end of a project.

Budget-cutting pressures reduce the budget allocated to architectural development (BA) below its indicated value during stage two. Figure 8 shows the indicated budget for architectural development. The indicated budget for architectural development is

the amount of money the firm would plan to spend during a given stage of architectural development if there were no budget cuts. The low return on sales during stage two causes the firm to cut the budget allocated for architectural development below the indicated budget.

There are three pressure that influence the decision to build an architecture: the effect of time on the decision to build an architecture (ETDBA). the effect of return on investment on the decision to build an architecture (ERDBA), and the effect of organizational delay on the decision to build an architecture (EODDBA). The following analysis considers each of the pressures individually. Figure 9 shows the behavior of each pressure.

The pressure to start the architecture increases as its feasible completion date slips back in time. At the start of the simulation, the perceived technology will not allow the completion of a satisfactory architecture in time to meet the initial deadline. The firm extends the deadline to give the R&D group more time to develop the architecture.

At the start of the base run, the potential architecture's low return on investment creates a pressure to postpone architectural development. The pressure results from the architecture's high non-recurring development cost and consequent low return on investment (ROI). The pressure to delay starting the architecture diminishes over the course of the base run as the architecture's ROI improves.

The ROI improves for two reasons. First, market growth increases sales and makes a reduction of manufacturing cost more profitable. The total saving from a lower per unit manufacturing increases proportionately with sales. Second, architectural development cost falls with technological progress.

The pressure to delay architectural development generated by organizational factors diminishes over time. As discussed above, the firm gradually becomes convinced that a new architecture is necessary and feasible.

The fraction of revenue allocated to R&D (FRDB) declines during stage two because of budget cuts. The firm fails to meet its return on sales goal during most of stage two and low profit causes the reduction of R&D spending.

In total, higher sales and lower average manufacturing cost (AMC) are no longer sufficient to maintain profit growth during stage two. The forces pushing profit upward are offset by lower price and the higher budget allocated to architectural development (BA).

Profit rebounds during stage three when the architecture is completed. The new architecture allows the development of many new products with low manufacturing costs. The new products cause a rise in market share and sales. Average manufacturing cost falls as the new products flow into products in production. Total R&D spending

declines because the firm no longer incurs architectural development costs. The combination of higher sales, lower average manufacturing cost, and lower R&D spending dominates falling price and forces profit up.

Inherent delays in the R&D system cause the upturn in profit to lag the completion of the new architecture. The firm finishes the new architecture at month 97, but Figure 6 shows that profit continues to fall until month 118. The profit upturn lags the completion of the architecture for two reasons. First, the firm continues to develop products with the old architecture even after the new architecture is completed since instantaneous conversion is impossible. For example, when the VLSI architecture is completed, the firm will still develop some LSI products. The number of VLSI products introduced into development will increase rapidly over time. The firm needs preparation time before it can build products based on VLSI. Secondly, products based on the new architecture are not developed instantly but take time. The new products only increase profit after they become products in production (PIP) and are sold.

Overall, the architectural development process dominates the behavior of profit during each stage of the base run. During stage one, the firm has just finished an architecture. Product development is relatively inexpensive and most engineering problems are easily solved. Management accepts praise for operating a profitable company, while the R&D group congratulates itself for successful engineering

projects. Stage two marks the beginning of hard times for the firm. Product development costs begin to rise as the old architecture becomes less suited to product needs. Management starts to wonder if the R&D group has lost its stuff. Falling profitability generates tremendous pressure to produce a good "bottom line" and the firm may reduce "non-essential" spending such as R&D. Stage two is the critical decision period for the firm. During stage two, the firm must select the design for a new architecture. Profit will continue to fall until after the new architecture is completed. Therefore, the firm must develop an architecture that yields a reasonable margin as soon as possible. Otherwise, a large decline in profitability can trigger a vicious circle in which a fall in profitability leads to lower R&D spending and further declines in profitability. Lower R&D spending can only slow down the development and implementation of the new architecture. The decisions made during stage two determine the outcome of stage three. If the firm efficiently makes the transition to a new architecture, stage three will be a period of renewed profitability. However, in the base run, the firm selects an expensive architecture and then cuts development spending. The implementation of the architecture comes too late to significantly improve profitability.

V. POLICY ANALYSIS

This section isolates some of the policies that can increase the profit generated by non-recurring development spending. Each policy will be simulated and the results compared to the base run. The paper then explains why each policy is effective.

A. Budgeting

The first policy considered deals with the R&D budget. The purpose of the analysis is to determine how budget cuts affect the long-run profitability of development spending. A simulation is performed in which the firm does not reduce the R&D budget when it fails to meet its return on sales goal.

The policy run uses a budget policy that differs from the base run policy. In the base run, the fraction of revenue allocated to the R&D budget (FRDB) and the budget allocated to architectural development (BA) are affected by the effect of cost cutting on the budget (ECCB). The effect of cost cutting on the budget reduces the R&D budget if the firm fails to meet the short-term profit target. In the policy run, the effect of cost cutting on the budget is not active. The policy change causes R&D spending to be higher in the policy simulation.

The behavior of profit in the policy run differs from the base run in two important ways. The first difference is that profit

is higher in the base run from month 33 until month 105. Figure 10 compares profit in the base run to profit in the policy run. The second difference is that profit turns up earlier and reaches a higher final value in the policy run. Profit starts to grow at month 108 in the policy run as opposed to month 118 in the base run. Profit reaches 15 million by the end of the policy run versus 3 million in the base run. Cumulative profit is 22 million or 39% higher in the policy run.

The short-term effect of higher R&D spending differs significantly from the long-term effect. In the short term, the higher R&D expense directly reduces current profit. However, in the long term, extra R&D spending significantly increases profit. A larger R&D budget supports more products in development. Once completed, the additional products increase market share, profit, and the R&D budget. After the new architecture is completed the extra products also drive down average manufacturing cost.

The level of R&D spending is particularly critical following the completion of an architecture. Rapid implementation of a new architecture requires significant R&D spending. Falling price limits the period of time when a new architecture generates high profitability. This period of time is the architecture's technological window. In order to fully exploit the potential benefits of a new architecture, the firm must complete the architecture and its derivative products early in the technological

window.

In contrast, the R&D budget policy guarantees that spending will be low after the new architecture is finished. This is because profit does not improve until after the products developed with the new architecture begin to lower both development and manufacturing costs. Low profit reduces the firm's ability and willingness to spend on R&D. The firm fails to spend on R&D because profit is low. Profit is low because of low R&D expenditures. Figure 11 shows that the effect of cost cutting on the budget, which indicates the degree of budget reduction, never returns to its initial value during the base run. Cumulative profit in the base run is 40% lower than in the policy run. The relatively low base run profit shows that the firm wasted much of the potential profit from the new architecture.

The above analysis does not imply that unlimited R&D spending is an acceptable policy. R&D spending may be unproductive and certainly no part of the firm should receive a blank check. However, following the completion of an architecture, R&D spending is highly productive. The key point is that the budget system generates tremendous pressure to cut essential R&D spending at exactly the wrong time.

One fairly obvious question is why would a firm fail to make the neccesary R&D expenditures? Management feels pressure to reduce R&D outlays due to the difference between the short- and long-run

impacts of development spending. Profit in the base run is higher than in the policy run for about four years. A manager interested primarily in the short run might reduce development spending to increase short-run profit.

The temptation to reduce current expenditures is especially great given the short time managers stay at the same firm. A manager who decides to make the necessary investments would have to stay with the firm for at least four years before he would benefit from the larger profits earned by a new architecture.

Judging from the R&D literature, the problems caused by the short-term perspective are extensive. In a recent article, the president of a high technology firm remarked:

> "The root cause of the present and future decline of U.S. technological prominence is a temporal mismatch between the natural pace of innovation and the time horizon of most U.S. industrial corporations.... The time horizon is one year with occasional exceptions extending out to three years and rarely five years. The ubiquitous role is that every organizational element of the corporation must be judged "profitable" within this time frame."[6]

The same article described an example of the cost cutting behavior observed in the model,

> "The sales department of a major manufacturer recently oversold their production capacity. The division manager, under the gun of this year's profits, laid off some 25% of the design

> engineering department, at a time when the design load was already excessive, in order to guarantee a profit this year."[7]

The important point made in this section is that a common R&D budgeting policy is counterproductive in the long run. The maximum pressure to reduce development spending occurs when the firm finishes the new architecture. If the budget reductions take place, the firm will fail to develop the required products and will miss the technological window. Missing the technological window wastes much of the potential benefit gained by developing the new architecture.

B. Improved Technological Information

This section analyzes the effect of more recent information about potentially cost saving technologies. Timely information about appropriate new technologies should improve profitability. The particular firm studied based its architecture on semiconductor technology obtained via the semiconductor industry. Over time, technological progress reduces potential development and manufacturing costs. A close relationship with semiconductor producers informs the firm about lower cost methods.

In the model, the policy change is implemented by shortening the time to perceive the effect of technology (TPET). The time to perceive the effect of technology is the firm's delay in learning about new cost-saving technologies. Faster perception of available technologies can be accomplished in a variety of ways in an R&D-based organization. One option would be to form a product planning or

technology assessment team charged with investigating new technologies. The team would include representatives from marketing, R&D, manufacturing and other relevant areas. Information generated by the group would be an important input into the strategic planning and product development processes.

A second policy would be a close association with a firm that supplies critical technologies. The firm studied is a division of a major corporation that also owns a semiconductor producer. The firm and the semiconductor division have developed a close relationship operational in R&D activities. The firm's management believes that communication with the semiconductor division gave it a significant jump on the market in the development of the VLSI architecture.

A third policy would be to set up a cooperative design laboratory with a supplier of basic technology. For example, the firm studied operates a design laboratory in conjunction with its parent company. The lab has enabled the firm's engineers to learn about advances in semiconductor capability. Further, the cost of the cooperative laboratory has been relatively low.

In the policy run, profit turns up earlier and reaches a higher level than in the base run. Figure 12 compares profit in the policy run to profit in the base run. With a shorter time to perceive the effect of technology, profit turns up at month 105 as opposed to month 118 in the base run. Profit is significantly higher in the

policy run from month 96 until the end of the simulation.

The lower architectural development cost increases profit in the policy run. The development cost of the architecture in the policy run is 2.5 million compared to 4.7 million in the base run. Lower development cost has two impacts on profit. First, development spending is an expense and reduced period expenses increase profit. Second, the architecture is developed more quickly and faster development also enhances profit. In the policy run, the architectural engineering requirement is smaller and the firm finishes the architecture sooner.

There are two reasons why development cost is lower in the policy run. First, at any given time the firm may select a less costly architecture. Development cost is lower because the firm knows about the less expensive alternative. The second reason for the lower development cost stems from the way the firm decides to develop an architecture. Recent information about available technologies can prevent the firm from making a panic decision and developing an overly costly architecture. Because of falling margins, the firm feels more pressure to start the architecture if it believes that the architecture will take a long time to implement. In the policy simulation, the firm knows about an architecture with a shorter development time. Consequently, there is less pressure to start development and the decision to develop an architecture comes later. Technological progress reduces development costs while the firm waits to make a

decision. In the policy simulation, the extra waiting reduces the architecture's cost by 17%.

The policy simulation highlights a little-explored opportunity to improve profitability. The firm's long-run performance depends on how quickly it develops an architecture that lowers both recurring and non-recurring cost. Continuous technological progress reduces the time and development cost required to reach a given manufacturing cost. The firm's ability to exploit technological progress depends on how easily ideas penetrate the R&D group. The paper has argued that policies that enhance the transfer of technological informaton have high leverage for improving profitability. However, the benefits of current technological information are not fully realized until many years into the future. Most of the extra profit generated by faster and less expensive architectural development comes after the architecture is completed. Management may be reticent to adopt policies that yield benefits outside the normal one-to-five-year planning horizon. A recent article by Dean claims that this is a general characteristic of American management.

> "When I visited Mitsui in Japan I was proudly shown a new and very large 50,000 kilowatt blast furnace blower. I examined it closely and discovered an enormous example of a modern aircraft engine's axial compressor with every stator row adjustable for peak performance and flexibility. It was obvious on inspection and upon querying the Japanese engineers that they had been dedicated students of U.S. aircraft engine technology. In contrast, the builders of U.S. heavy turbomachinery almost never invest in technology except when designing to order. The technologists of this

> industry are generally uninformed about aircraft engine technology and indeed incapable of practicing the sophisticated technology even if they appreciated it. There is nothing in the U.S. heavy turbomachinery industry which approaches or even promises to approach in the next five years the technical level (and, I will warrant, the economic level) of this Japanese product."[8]

Analysis of the model demonstrates that firms are overlooking an important opportunity.

The concept of the technological gatekeeper, as developed by Allen, has direct relevance to the process of crossing a technological discontinuity.[9] Allen argues that technical information from the outside environment filters into an R&D organization via a "gatekeeper." A gatekeeper is an engineer, scientist, or manager who, "mediates between his organizational colleagues and the world outside, and he effectively couples the company to the scientific and technological activity in the world at large." Allen also analyzes some of the factors that determine the gatekeeper's effectiveness. The list includes the structure of the organization, geographical location, and how easily an engineer can meet his colleagues.

The analysis of the model leads to two points that are relevant to the technological gatekeeper. First, the gatekeeping function is absolutely critical to the success of the high technology company. In both the model and the real firm, general technological progress can reduce the cost and development time of an architecture. The importance of rapid architectural development has been stressed

throughout this paper. Second, the perceived importance of the gatekeeper is likely to vary over time. Shortly after the firm finishes an architecture, product development is relatively easy. Technological problems are manageable because the architecture is well suited to product needs. During this stage, the R&D group will feel competent and may not feel it requires much outside information. For the R&D engineer, this is a period of normal science. However, as the architecture ages, the technical problems of product development grow more complex. During this time, the network of gatekeepers becomes critical to the search for a new architecture.

The gatekeeper is also important immediately after a new architecture is finished. The gatekeepers may be responsible for training other engineers in the implementation of the new architecture. The role of the gatekeeper in training other engineers is discussed in the next section.

C. Faster Ramp Up Policy

This section analyzes policies that hasten the transition to a new architecture. After the firm completes an architecture, there is a delay before the architecture can be used to develop products. The delay corresponds to the time required to train engineers, plan the type of product to be produced, and make sure that the required materials and manufacturing equipment are available. In the industry jargon, preparing to use a new architecture is called "ramping up." The following simulation tests the impact of a faster ramp up.

In the model, the faster ramp up run is implemented by increasing the fraction of products produced with the primary architecture (FPPA). The fraction of products produced with the primary architecture is the fraction of the product generation rate (PGEN) that consists of products based on the primary architecture. For example, assume that ten new products are put into development during a given year. The fraction of products produced with the primary architecture is one-half if five of the products are based on the primary architecture. During the first six months after a primary architecture is finished, half of the products put into development might be based on the primary architecture. During the second six months, 75% of the products put into development might use the primary architecture. The policy run makes the fraction of products produced with the primary architecture higher for any given amount of time since the primary architecture was completed.

In the real firm, several policies could shorten the transition to a new architecture. First, as many product planning tasks as possible should be finished prior to the architecture's completion. Any tasks that can be done before the architecture is finished will shorten the ramp up time. Second, the firm should stress training the engineers who will implement the new architecture. Once the architecture is near completion, the firm could assign an engineer who had been working on the architecture to train other engineers. Sufficient engineers should be available to develop the products when the new architecture is finished. Third, the firm

should improve the efficiency of the product planning process. For example, conflicts between R&D and marketing cause many needless delays in new product development. Conflicts might be reduced through the use of third-party intervention; a third party from outside marketing and R&D departments would mediate disputes about new product specifications and accelerate the process of compromise between the conflicting parties.

Profit turns up earlier and reaches a higher final value in the policy run than in the base run. Figure 13 shows the comparison of profit between the two runs. Profit turns up at month 111 in the policy run as opposed to month 118 in the base run. Profit reaches 7.5 million by month 144 in the policy run versus 3 million in the base run.

The faster ramp up run demonstrates the importance of good planning. In this context, good planning means doing all of the tasks required to quickly implement a new architecture. Perhaps the most important task is training the engineers to develop the products based on the new architecture. The transition to a new architecture inevitably changes the engineering skills required to build a product. Generally, the labor market for persons with the new skills will be extremely tight. The successful implementation of the new architecture depends on how quickly and effectively the firm can re-educate its existing personnel. Otherwise, if the requisite engineering skills are not available, the architecture will be

implemented too slowly and the firm will squander a tremendous opportunity to improve profitability.

D. ROI Policy and Product Diversification

Analysis of the model provides a strong rationale for product line diversification. The firm's problems begin with the declining utility of the old architecture. As the architecture ages, profitability starts to fall. The initial decline in profitability triggers a vicious circle in which lower profitability leads to lower R&D spending and still lower profitability. A second product line could sustain profitability while an architecture in the first line is being developed. Diversification would help circumvent the trap created by the initial decline of profitability.

The model analysis needs to be differentiated from the finance literature that also stresses diversification. Financial analysis views diversification as a means of neutralizing random profit downturns. The model analysis argues that the structure of the R&D system causes predictable periods of low profit. The argument in favor of diversification is much stronger when low profit is viewed as an outcome of th system's structure.

The high ROI figure in the basic product line could blind the firm to the need for diversification. A company might ask why it should diversify when investment in its basic business remains so profitable. Investment in an entirely new line will often have an ROI

that is is much lower than the ROI in the basic product line. The reason for the difference in ROI is that the firm already has a substantial share of a large market in the basic product line. In the early stages of a new product line, sales volume won't be adequate to generate "box car" figures. The firm might avoid new products because their return compares poorly to the return in the basic line.

The cyclical nature of profit in a single product line company provides a strong justification for diversification. The firm must consider both ROI and the dynamic behavior of profit when deciding to diversify. Clearly, the firm does not want to invest in low return projects. However, the firm should not insist on gigantic return figures either. Investment in a product line with a reasonable but relatively low ROI can be justified by the need to damp the cyclical behavior of profit.

E. R&D Productivity Policy

This section examines a series of policies designed to increase R&D productivity. As discussed above, in about 1979, the firm became concerned with cost and schedule overruns associated with many new product developments. The firm considered a number of programs designed to improve R&D productivity: the firm went through several managerial reorgnizations, put its engineers through team building and motivational courses, and considered several new financial incentive programs. It does not appear that any of these measures has been particularly successful. This section uses the

model to explain why even a well-designed productivity enhancement program may fail if it is implemented at the wrong time.

In the model, the policy test is implemented through an exogenous change in R&D productivity. In the policy run, it is assumed that at month 50, the firm adopts measures that increase engineering productivity by an arbitrary 15%. The productivity gain applies only to engineers working on products and not to engineers working on the architecture.

In the policy run, profit is higher than in the base run over the entire simulation. Figure 14 presents a plot that compares profit for the two runs. However, the magnitude of the difference in profit varies significantly in time. Shortly after month 50, profit in the policy run rises somewhat above profit in the base run. The difference in profit becomes negligible during the period of profit decline. However, following the completion of the architecture the difference in profit between the two runs is quite pronounced.

Profit is higher in the policy run because engineers are more productive and turn out additional products. However, from month 78 until month 120, the effect of the productivity program is swamped by two factors: First, the number of man-months and the cost of each man-month required to develop a product continue to grow as the architecture ages. The cost of product development becomes so large that a 15% increase in productivity does not lead to many more product

completions. Second, the productivity program does nothing to lower manufacturing cost which is the root cause of declining profit.

The policy change becomes extremely significant following the completion of the new architecture. After the architecture is finished, average product development costs begin to fall and the 15% increase in productivity helps increase the rate at which the new generation of products gets to market. Notably, the impact of the policy is no longer being offset by rapidly increasing product engineering requirements.

The simulation experiment highlights the danger that the firm will abandon a successful policy because it is introduced at the wrong point in time. At month 50, the firm implements a change that is expected to increase R&D productivity. In the short run, from month 63 until month 81, the policy appears to succeed. After month 81, both profit and R&D productivity go into a tailspin. The firm may be tempted to abandon the program because it no longer seems to work. The temptation will be especially strong if the program is expensive (for example, an incentive system), or counter to management's need for control (for example a system of decentralized decision making). Elimination of the policy becomes even more likely if the firm changes management because of the decline in profit. The simulation reveals that the policy makes a significant difference after the architecture is completed. Most of the policy's potential benefit will be lost if it is abandoned to quickly.

F. Performance Indicators

This section analyzes two performance indicators that are commonly applied to high technology companies: "quarterly profitability" and "fraction of revenue invested in R&D." The analysis assumes the perspective of a corporate manager who must assess the performance of a division. The firm discussed in the paper is a division of a large Fortune 500 company and faces quarterly performance reviews. The important question addressed in this section is whether the performance measures contribute to long-term profitability. This is important for several reasons. First, performance measures should inform upper management if things are going badly so that the necessary changes can be made. Second, management compensation is often tied to performance measures. Is the firm, by implication, rewarding short-term performance at the expense of long-term corporate health?

The first measure considered is short-term profit. Short-term profit can be measured several ways. A firm could use return on assets, return on sales, quarterly dollar profit or some combination of the three. Quarterly dollar profit is the measure used in this simulation experiment.

The simulation experiment is designed to reveal whether a policy change that significantly increases long-run profit would be measured as successful by a quarterly profit standard. At month 100, the base run policy of reducing the R&D budget in response to low

profit is eliminated. R&D spending is restored to 6% from 3.5% of total revenue.

The results of the policy run illustrate a clear example of "worse before better" behavior": Figure 15 presents a comparison of profit between the policy run and the base run. The immediate effect of the policy change at month 100 is to drive profit in the policy run below profit in the base run for about 14 months. Ater month 114, policy run profit grows to more than double base run profit. Cumulative profit for the entire simulation is 16% higher in the policy run.

The "worse before better" behavior exhibited in the policy run stems from the delayed impact of development spending. The products developed with the extra budget take time to reach the marketplace. The additional R&D spending beginning at time 100 does not have a significant effect on profit until over a year later.

A system that rewards managers on the basis of quarterly profit would discourage the implementation of the policy. A far-sighted executive might look past 14 months of lower profit (and bonuses) and base decisions on a longer-term view. On the other hand, an executive who plans to leave the firm or at least his current position within a year might take the money and run. In any case, the important point is that the measurement scheme rewards counterproductive behavior.

The importance of R&D to the firm's success points to some measure of R&D spending as a standard by which a firm can be evaluated. A commonly used number is the fraction of revenue spent on R&D. A firm that spends a large fraction of its revenue on R&D is thought to be providing for its long-run profitability. -

This section deals with two questions that come out of an empirical controversy. At least two recent studies have found a positive correlation between the fraction of revenue spent on R&D and profitability.[10] The firm's planning director related that it is the accepted wisdom in the industry that companies should spend between five ten percent of revenues on R&D. However, a study conducted by Booz-Allen found no relationship between profitability and R&D spending.[11] The first important question is whether or not there is a relationship between R&D spending and profitability. The second question is how can the different empirical estimates be reconciled. A simulation of the model will be used to analyze both questions.

The base run of the model is compared to the behavior of what will be called the "healthy firm." The healthy firm develops an architecture at a lower non-recurring cost and restrains itself from cutting the R&D budget. In the model, the healthy firm is created by shortening the time to perceive the effect of technology and eliminating the budget cuts. Notably, the health firm earns almost twice as much profit over the course of the simulation.

Figure 16 shows a plot that compares the fraction of revenue spent on R&D in the two simulations. The healthy firm spends a smaller fraction of revenue on R&D from month 30 until month 72. From month 72 until the end of the simulation, the healthy firm spend a larger fraction of revenue on R&D.

The model suggests that there is no necessary correlation between the fraction of revenue spent on R&D and profitability. From month 30 until month 72, comparative R&D spending is dominated by the cost of the new architecture. The healthy firm develops an architecture with lower non-recurring cost and spends less on R&D than the firm in the base run. After month 72, comparative R&D spending is dominated by budget cutting in response to low profitability. R&D spending by the healthy firm is higher than in the base run because the healthy firm doesn't cut the R&D budget. Clearly, the firm may spend a large fraction of its revenue on R&D either because it spends too much to develop an architecture, or because it is willing to invest in its future. The aggregate fraction of revenue spent on R&D cannot distinguish between the two reasons for spending.

The simulation also provides a possible explanation for the observed positive correlation between R&D spending and profitability. At month 100, one would observe that the firm spending a larger fraction of revenue on R&D earns a larger profit. At month 40, one would observe exactly the opposite relationship. If the average fraction of revenue spent on R&D was compared to average profit, the

correlation could be positive, negative, or zero, depending on the time period considered. The important point is that depending on the time when the measurement is taken, it would be possible to observe a false positive correlation. Without looking at the samples of the specific studies, it is impossible to know why a positive correlation was observed. All that can be said is that two studies can reach opposite conclusions because their sample were taken at different times.

The previous section dismissed quarterly profit and the fraction of revenue spent on R&D as meaningful performance indicators. The measures are inadequate because they are the behavioral results of policies that can be counterproductive in the long run. Simply stated, at any point in time, a bad policy can produce a good number and vice versa. The following deals with how a high technology company should judge the effectiveness of managers charged with the implementation of long-term strategic objectives.

The decisions made about the development of a new architecture are strategic as opposed to tactical. Two distinctions between strategic and tactical decisions are the length of time between a decision and its consequences and how easily the impact of a bad decision can be reversed. A strategic decision is characterized by a long lag between the decision and its consequences. For example, it was suggested that a cooperative design laboratory would be an extremely effective policy. The design laboratory might cost several

million dollars which is large in absolute terms, but small relative to the future payoff. The benefits of the design laboratory would not be felt until at least five years after it was instituted. In contrast, the impact of a tactical decision is felt much sooner. For example, the firm's sales manager must decide how to allocate sales effort between products. It is likely that a bad allocation would affect orders within a quarter or two. A strategic decision is also characterized by the difficulty of reversing a bad decision. For example, a decision not to establish the design laboratory can lengthen the architectural development cycle. A longer architectural development time leads to years of lower profitabiltiy. The effects of a bad tactical decision are easier to correct. For example, sales effort could be quickly reallocated if the original allocation does not work out.

The distinction between strategic and tactical decisions becomes crucial in selecting a proper evaluation scheme. Managers who are responsible for strategic decisons should be rewarded for long-run performance. Perverse decisions will result from evaluating strategic decisions with short-term measures. For example, quarterly profit targets might deter the establishment of a design laboratory that pays off five years later. The difficulty of a bad strategic decision makes the evaluation problem especially severe. Any decision that slows down the development or implementation of the new architecture will lower profitability for many years.

One solution to the evaluation problem comes from the firm's clear recognition and implementation of its strategic objectives. In the paper, strategic objectives have been defined by a careful examination of the firm and the construction of a detailed model. This paper has argued that efficiently crossing the technological discontinuity is perhaps the most important determinant of the firm's success. It has also been argued that there are policies that make the transition much easier. For example, the model suggests that a faster transition to a new architecture and better communication with the suppliers of basic technology are very high leverage policies. For each policy, some of the real world steps required for implementation were discussed.

A manager whose job includes strategic concerns should be judged on how well he implements the broad strategic objectives. In the case of the transition to a new architecture, a plan should outline how the R&D group plans to train engineers, acquire materials and capital equipment, and generally perform the tasks required to implement the products based on the new architecture. The specifics of the plan should be the responsibility of the R&D group. Implementation of the plan should be monitored quarterly by top management. Also, managers concerned with long-run strategic objectives should be compensated on the basis of long-run average profit. In the particular firm's case, the long run should span the development of an architecture and its replacement by the next generation. The time interval would be quite long--maybe 6-8 years.

The longer evaluation horizon would reduce the motivation to sacrifice the firm's long-term health for short-run gain. It is perhaps intersting to note that such policies counsel patience in an otherwise frenetic industrial environment.

VI. CONCLUSION

In review, the paper has used the experience of a specific firm to generate policies for improving R&D productivity. The analysis began by considering the circumstances of a specific firm. The firm suffered from declining R&D productivity manifested by cost and schedule overruns. The examination of the firm led to the concept of a technological discontinuity. The process of crossing a technological discontinuity, or what was called architectural development, formed the basis of a detailed simulation model. The model was used to highlight policies that improve profitability. The policy analysis led to three important conclusions. First, relatively simple and pracical policies, like a faster ramp up and more current technological information, can greatly ease the transition to a new architecture and improve profitability. Second, much of the firm's pain concerning R&D productivity comes from self-inflicted wounds. An R&D budget policy based on current profit can be counted on to provide the wrong result at exactly the wrong time. Third, short-term profit and the fraction of revenue spent on R&D were found to be poor performance criteria.

The concept of the technological transition relates some diverse observations about R&D productivity to the firm's goal of high profitability. Incentive systems, R&D budgeting, technological "S" curves, and gatekeepers, are frequent topics in the literature and these ideas have led to many important studies. However, it remains

unclear how these studies fit together and why they are important for profitability. Practicing managers are left with interesting empirical observations that are of unknown significance. The focus of this paper is much more operational. In order to be useful, ideas about R&D productivity must fit into a framework that explains how they affect profitability. It is only through such an organizing structure that meaningful change is possible. Hopefully, the model of the technological transition is a start at building the necessary framework.

An understanding of the danger and potential created by technological discontinuities could not be more important in today's economy. Recently, high technology firms have been the success stories of American industry. However, the Japanese, among others, appear ready to challenge traditional American strongholds such as data communications. It is exactly this type of competition that pushes a firm to the edge of its technological capabilities. Indeed, the Indians are coming up faster than ever. Increasingly, our economic future will depend on the ability to leap the technological chasm.

NOTES

[1] "Snafus that Delay New Products," Business Week, June 1, 1981, p. 110.

[2] ibid.

[3] A similar idea is described in "Picking the Right Technology Should Be First Priority," Research Management, July 1981, p. 8.

[4] Richardson, George P., "Managing R&D in a High Growth Company," Working Paper D-3321, System Dynamics Group, Massachusetts Institute of Technology.

[5] These conditions were deemed typical of many, if not most, developing high technology market segments.

[6] Dean, Robert C., "The Temporal Mismatch--Innovation's Pace vs. Management's Time Horizon," Research Management, May 1974, p. 12.

[7] ibid, p. 13.

[8] ibid, p. 15.

[9] Allen, Thomas J., "Communication Networks in R&D Laboratories," R&D Management, vol. 1, no. 1, 1970, pp. 14-21.

[10] See E.L. Reynard, "A Method for Relating Research Spending to Net Profits," Research Management, July 1979, pp. 12-14.

[11] "Despite Mixed Record, Firms Still Pushing for New Products," The Wall Street Journal, November 12, 1981, p. 31.

FIGURE 1

Company PROFIT AS A PERCENT OF ITS 1975 VALUE

FIGURE 2

REGENERATIVE LOOP

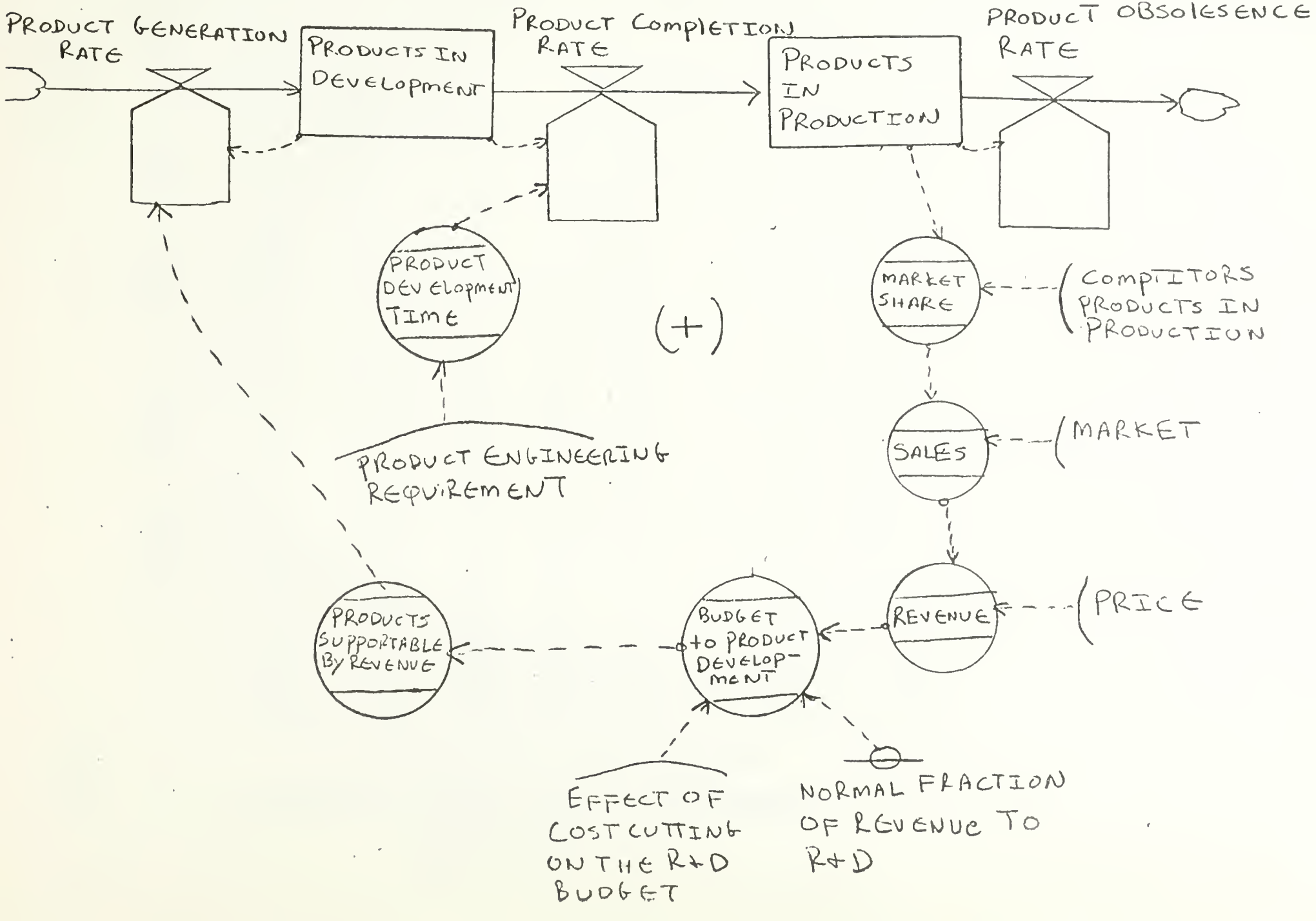


FIGURE 3

DECISION TO BUILD AN ARCHITECTURE

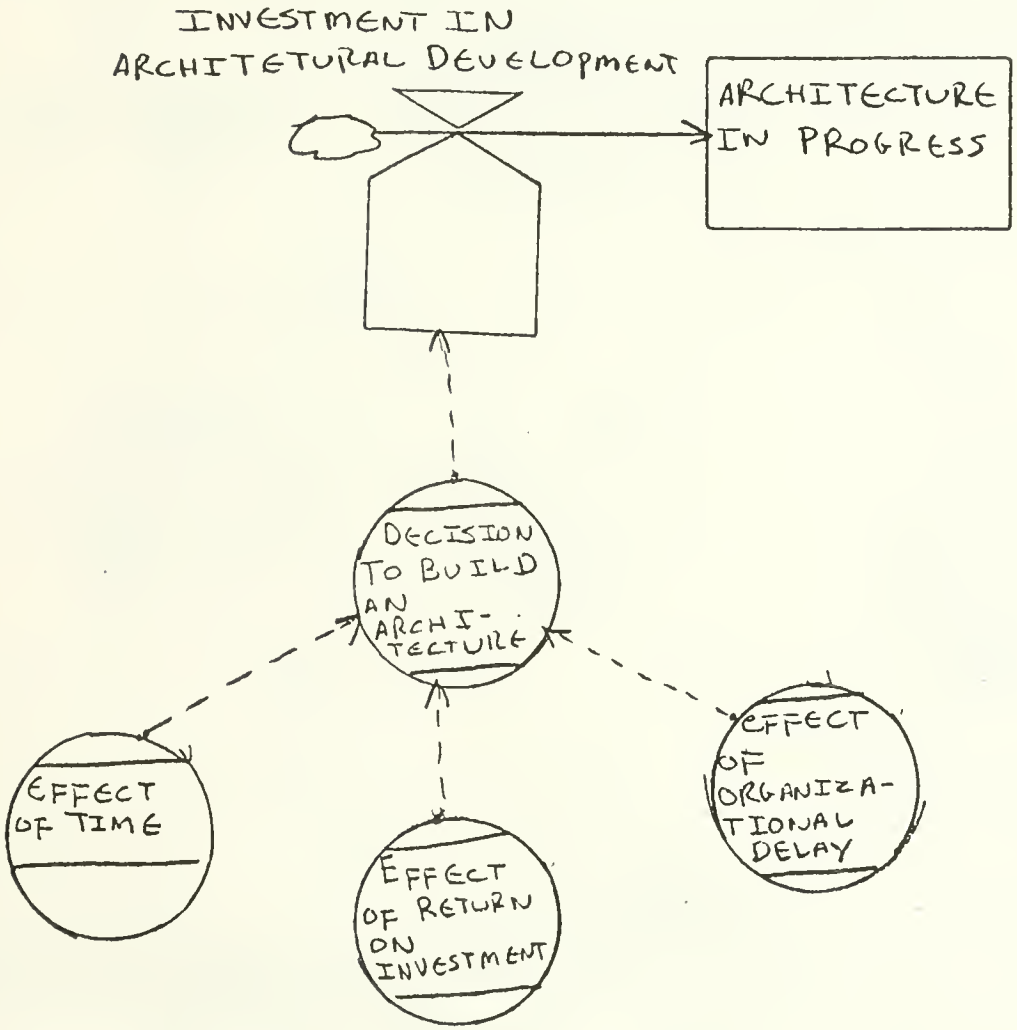

INVESTMENT IN ARCHITETURAL DEVELOPMENT
ARCHITECTURE IN PROGRESS
DECISION TO BUILD AN ARCHI-TECTURE
EFFECT OF TIME
EFFECT OF RETURN ON INVESTMENT
EFFECT OF ORGANIZA-TIONAL DELAY

FIGURE 4

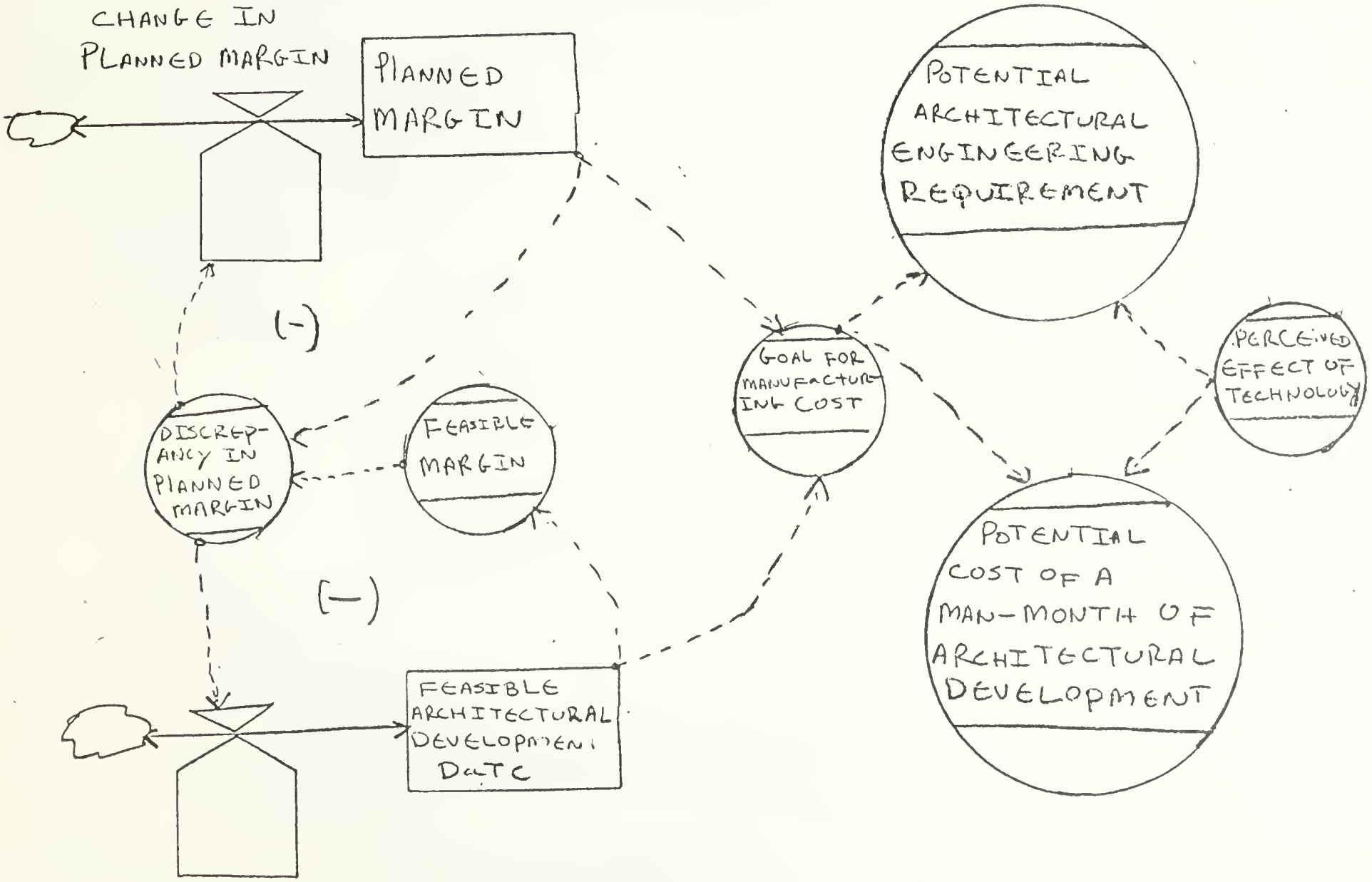

CHANGE IN PLANNED MARGIN
PLANNED MARGIN
(-)
DISCREP-ANCY IN PLANNED MARGIN
FEASIBLE MARGIN
(-)
FEASIBLE ARCHITECTURAL DEVELOPMENT DATE
CHANGE IN FEASIBLE ARCHITECTURAL DEVELOPMENT DATE
GOAL FOR MANUFACTURING COST
POTENTIAL ARCHITECTURAL ENGINEERING REQUIREMENT
PERCEIVED EFFECT OF TECHNOLOGY
POTENTIAL COST OF A MAN-MONTH OF ARCHITECTURAL DEVELOPMENT

FIGURE 5

TRADEOFF BETWEEN THE POTENTIAL ARCHITECTURAL ENGINEERING REQUIREMENT (PAER) AND THE GOAL FOR MANUFACTURING COST. (GMC)

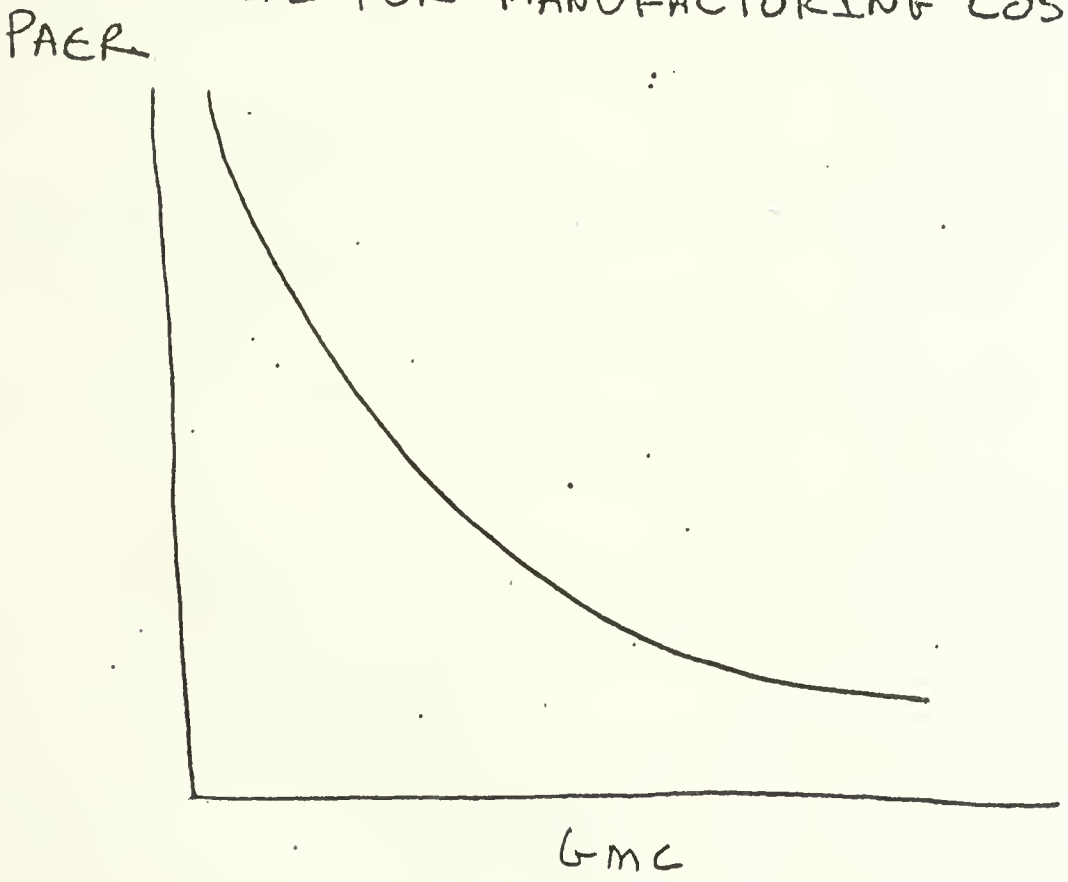


FIGURE 6
BASE RUN PROFIT

FIGURE 7

BASE RUN BEHAVIOR.

PRODUCTS IN DEVELOPMENT = 1

PRODUCTS IN PRODUCTION = 2

AVERAGE MANUFACTURING COST = 3

SALES = 4.

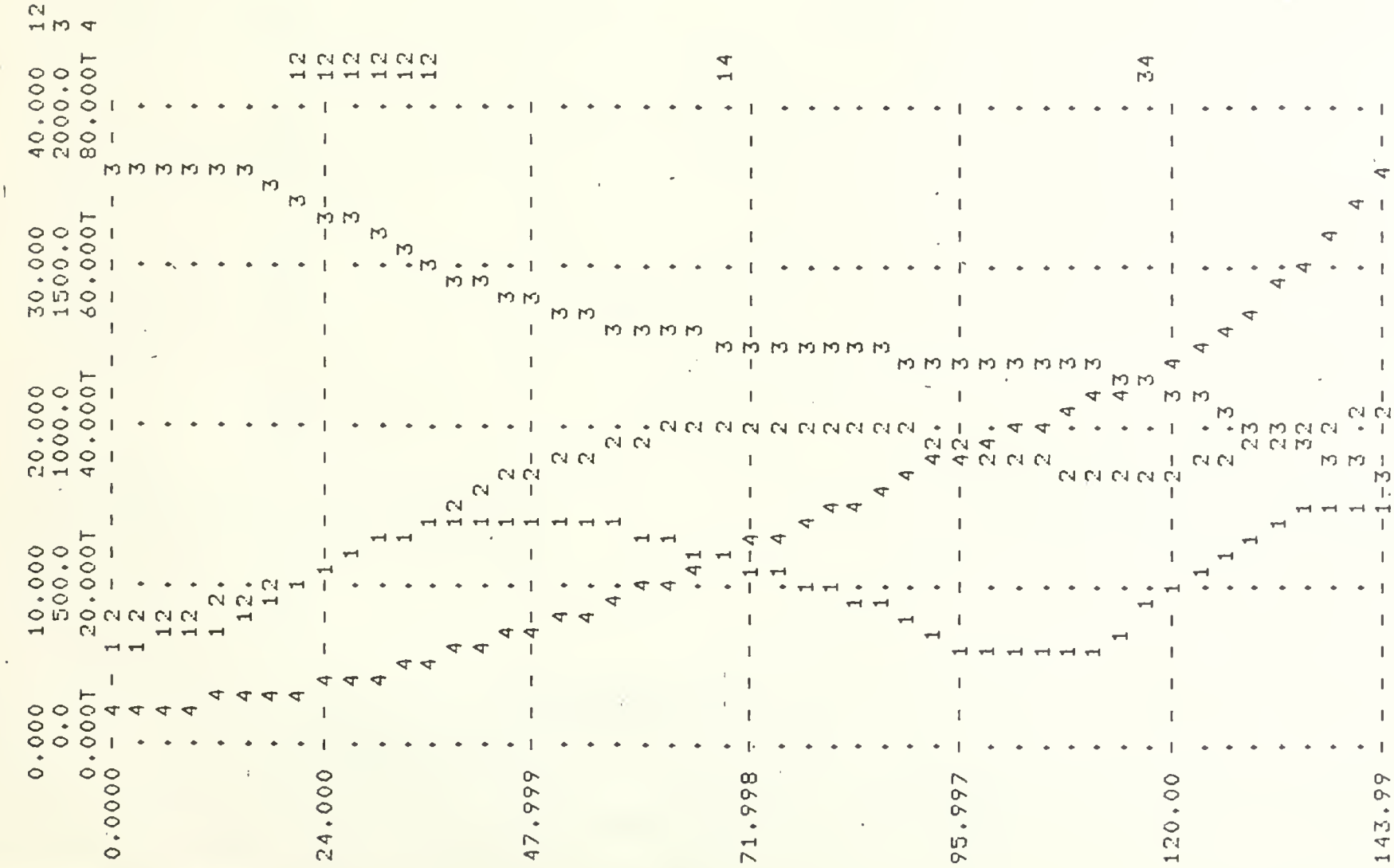


FIGURE 8

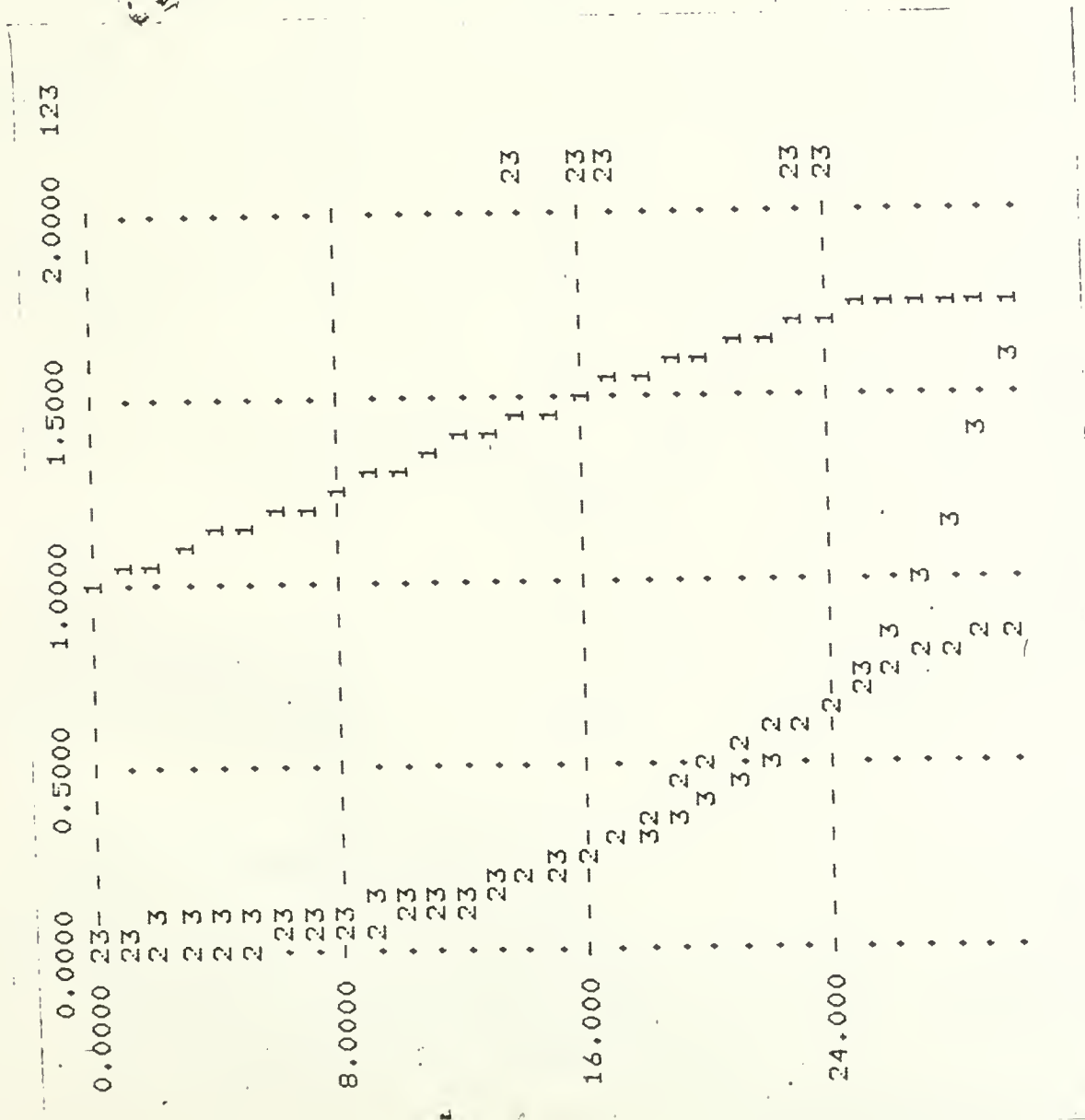
THE INDICATED BUDGET ALLOCATED TO ARCHITECTURAL DEVELOPMENT = 1
THE BUDGET ALLOCATED TO ARCHITECTURAL DEVELOPMENT = 2

FIGURE 9

THE EFFECT OF TIME ON THE DECISION TO BUID AN ARCHITETURE = 1

THE EFFECT OF ORGANIZATIONAL DELAY ON THE DECISION TO BUILD AN ARCHITUTURE = 2

THE EFFECT OF RETURN ON INVESTMENT ON THE DECISION TO BUILD AN ARCHITETURE = 3



Comparison of Base Run
Profit to "No Budget Cutting" Run Profit
No Budget Cutting Run Profit = 1
Base Profit = 2.

FIGURE 11

BASE RUN BEHAVIOR
OF THE EFFECT OF COST CUTTING
ON the BUDGET (ECCB)

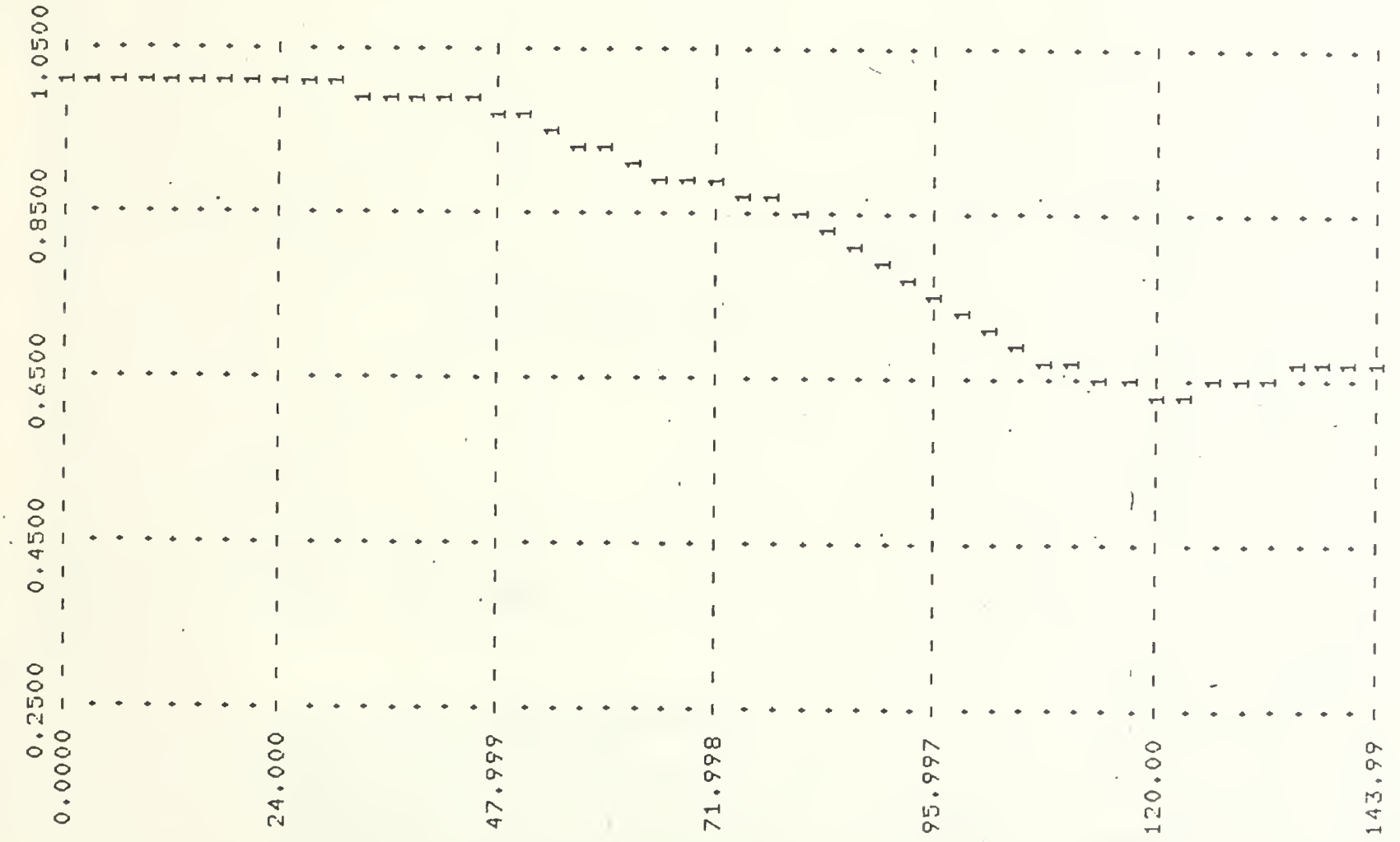


FIGURE 12

COMPARISON OF BASE RUN PROFIT TO A RUN WITH A SHORTER TIME TO PERCEIVE THE EFFECT OF TECHNOLOGY (TPET)

BASE RUN PROFIT = 1

SHORTER TPET RUN = 2

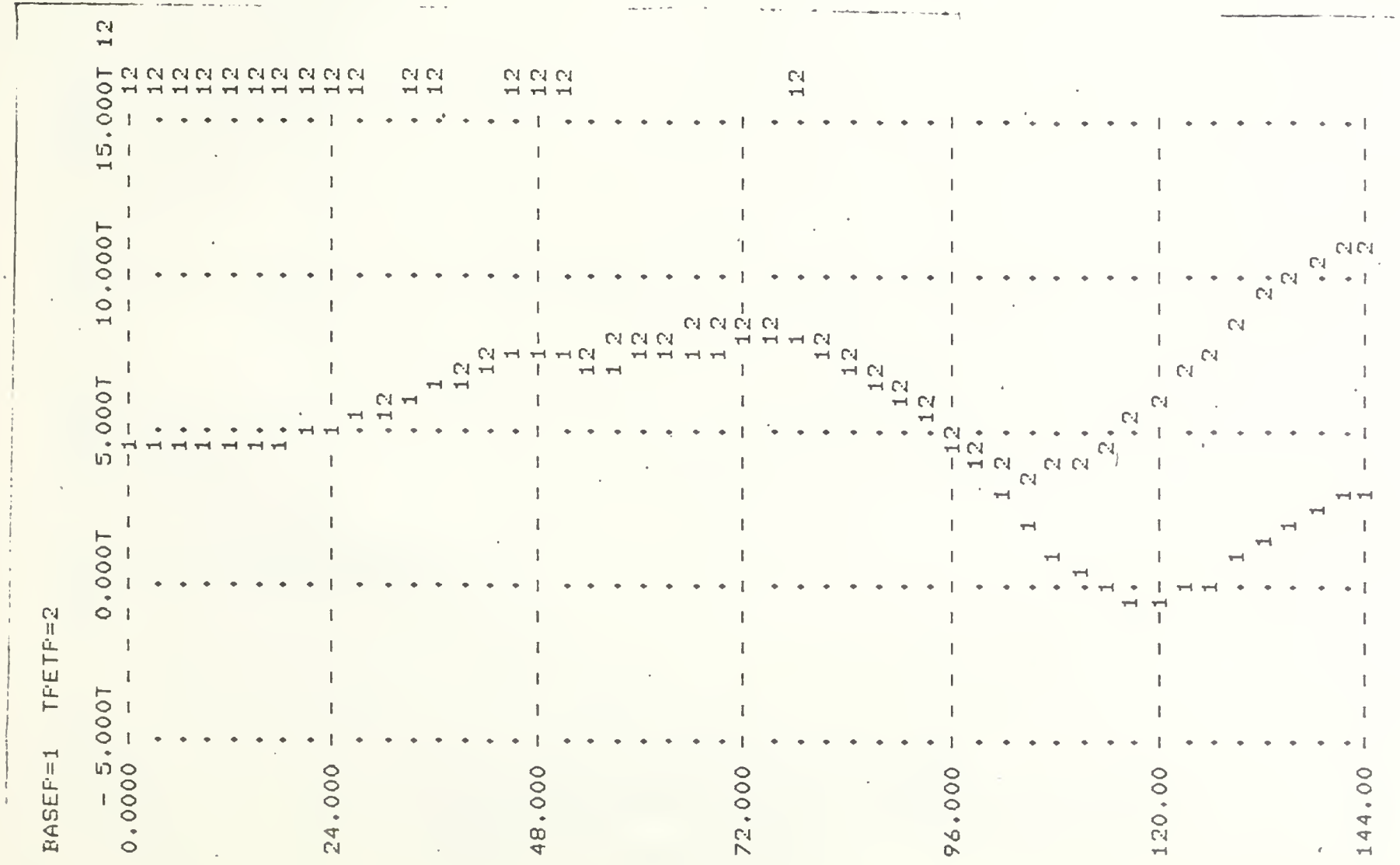
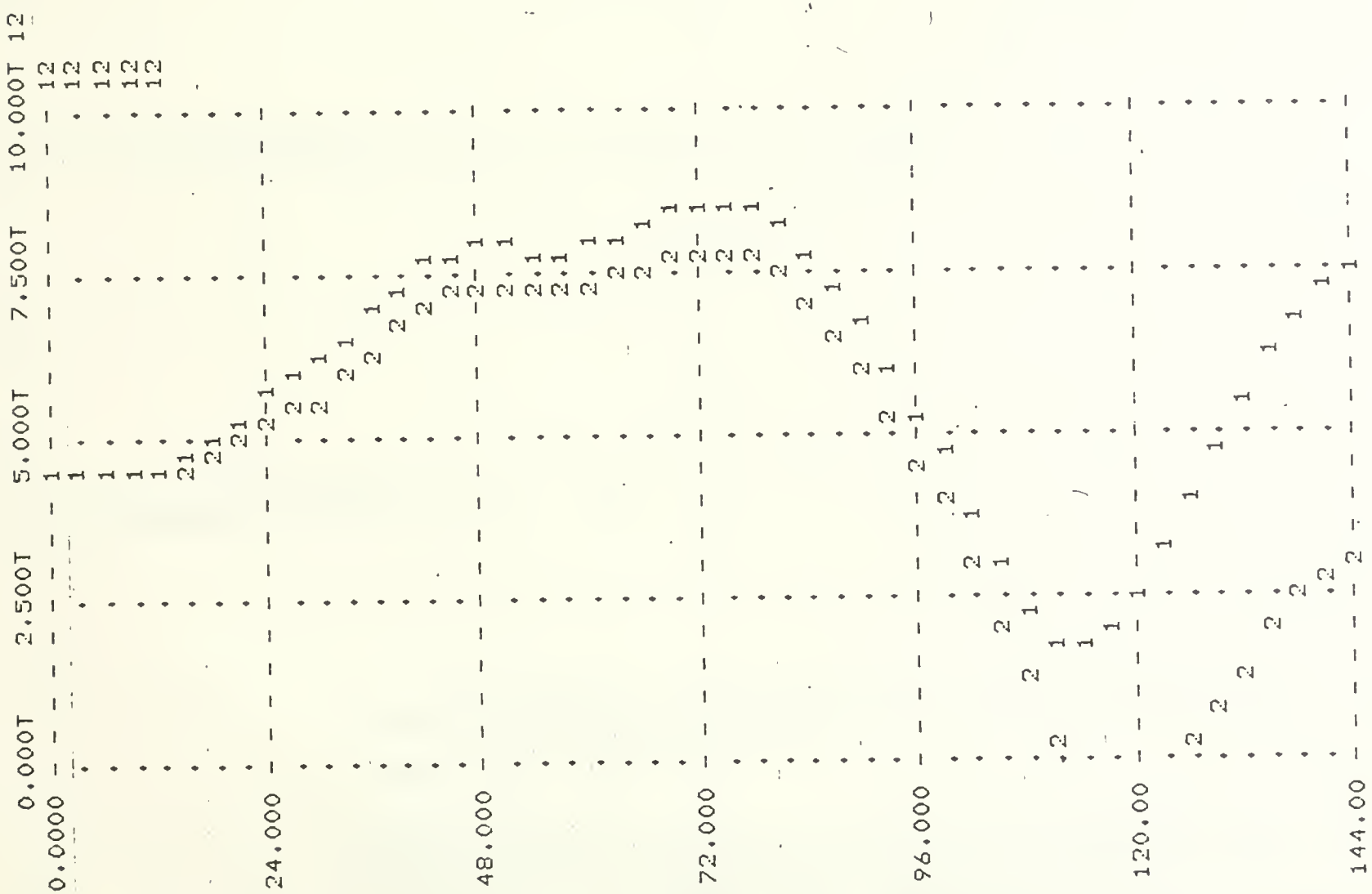


FIGURE 13

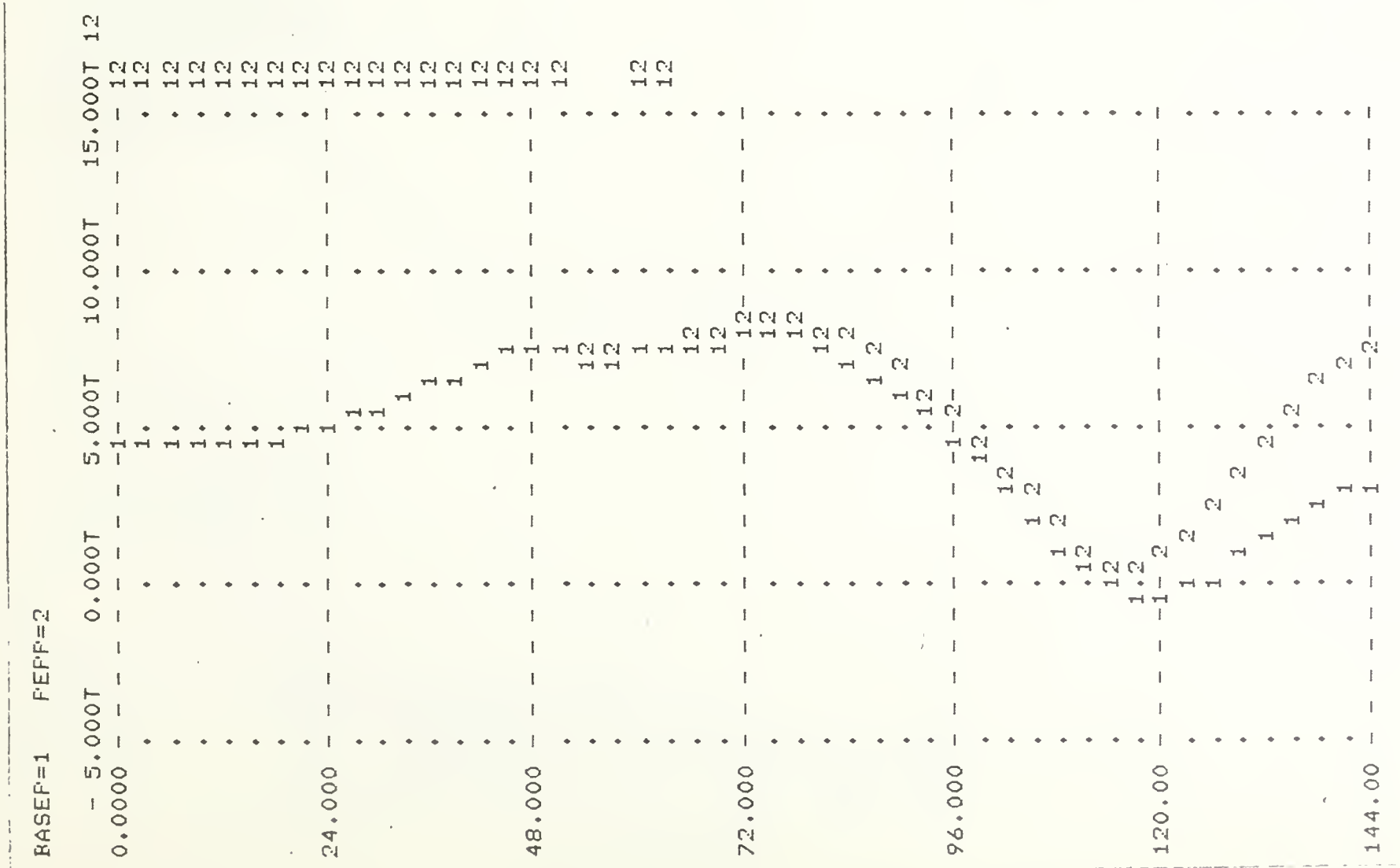
COMPARISON OF BASE RUN PROFIT
TO FASTER RAMP UP RUN PROFIT
FASTER RAMP UP PROFIT = 1
BASE PROFIT = 2



COMPARISON OF BASE RUN PROFIT TO PROFIT WITH A PRODUCTIVITY IMPROVEMENT PROGRAM

BASE RUN PROFIT=1

PRODUCTIVITY IMPROVEMENT RUN PROFIT=2



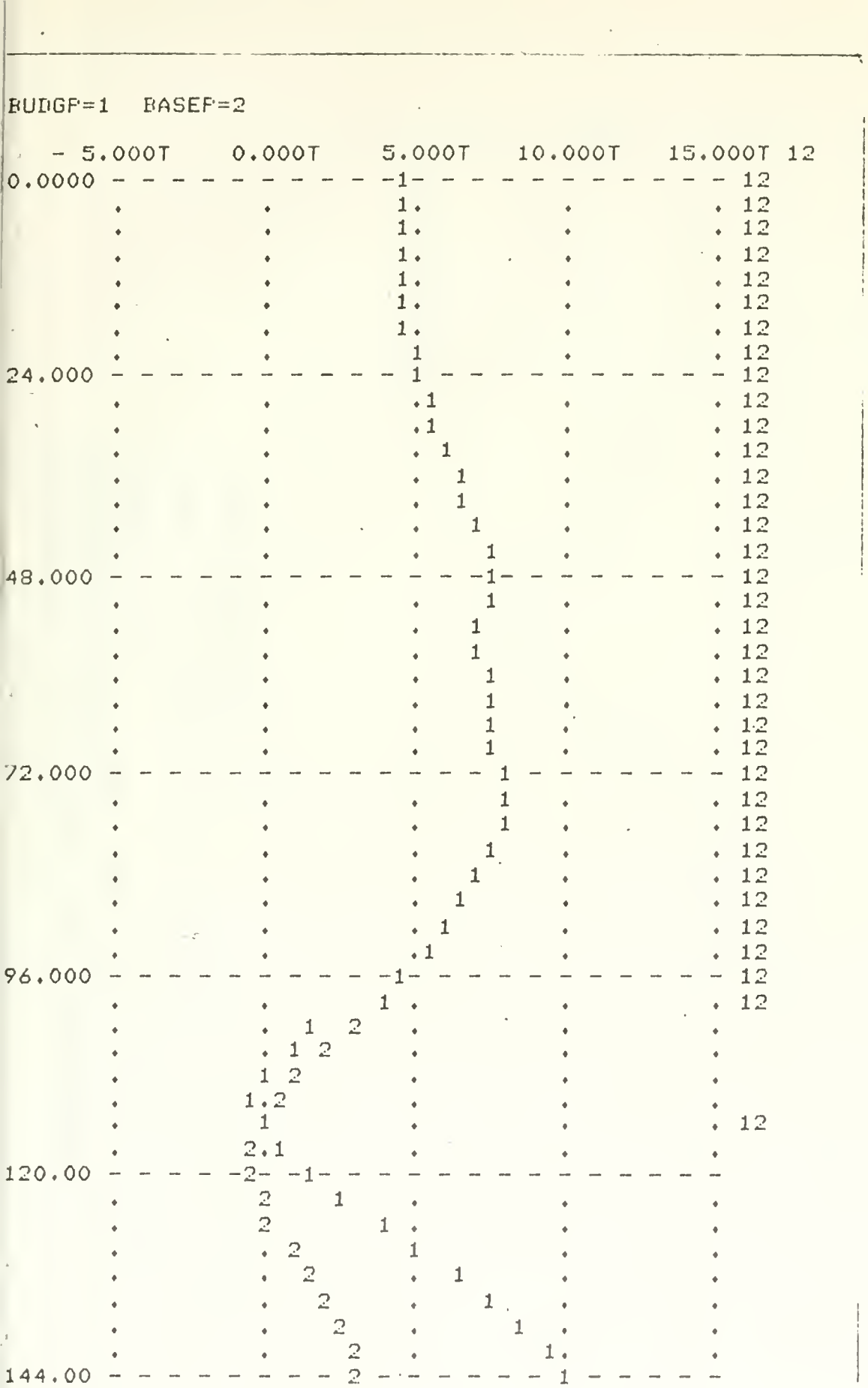


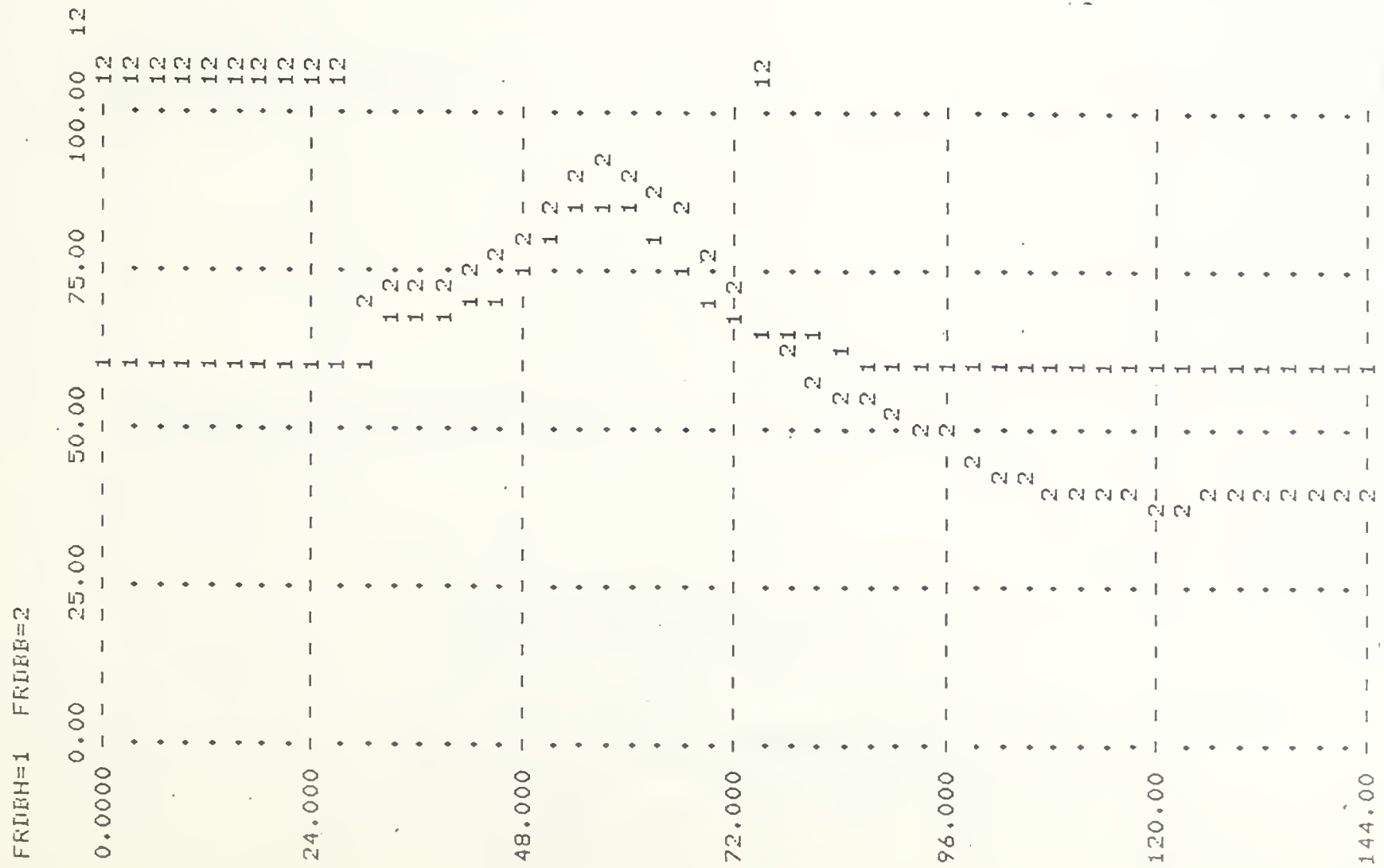
FIGURE 15

COMPARISON OF BASE RUN PROFIT TO PROFIT WHEN BUDGET CUTS ARE STOPPED AT TIME 100

BASE RUN PROFIT=2
POLICY RUN PROFIT=1

Comparison of Base Run Development Spending to Healthy Firm Development Spending

Base Run Fraction of Revenue Spent on R+D = 1
Healthy Firm = 2



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